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OOK IN PHYSICS

FOR

DARY SCHOOLS

BY

T. MUMPER, PH.D.,

E STATE NORMAL AND MODEL SCHOOLS
TON, NEW JERSEY

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IPA

A TEXT-BOOK IN PHYSICS

FOR

SECONDARY SCHOOLS

BY

WILLIAM N. MUMPER, PH.D.,

PROFESSOR OF PHYSICS IN THE STATE NORMAL AND MODEL SCHOOLS
OF TRENTON, NEW JERSEY

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MUMPER, PHYSICS.

W. P. I

PREFACE

This book embodies the results of an extended experience in adapting the text-book work of the first year in physics to the capabilities and the needs of secondary school pupils. In its preparation full consideration has been given to the pupil's knowledge and mental power, to the time available for text-book study, and to the proper aims in a beginners' course. The general plan of the book presupposes that before taking up the study of the text on any topic, the pupil has acquired a clear knowledge of the fundamental physical facts. This end must be reached both through the observation of common phenomena and by means of experiments performed in the class room and the laboratory. Carefully studied experiments are absolutely essential to the doing of good work in physics, but it is a grave mistake to assume that merely reading the *directions* for experiments constitutes either experimenting or a sufficient substitute for it. The obscuring of some of the most important parts of a discussion in the small type of a so-called "experiment" has been avoided. Detailed directions for experiments to be performed either by the teacher or by the pupil properly belong in a laboratory manual rather than in a text-book. The great variations in the apparatus equipment of the schools render the most of such directions valueless at best; and when directions are not used, their presence is a positive detriment in that it interrupts the continuity of the treatment. As will be readily noted, the book is full of suggestions which should lead to experimenting.

In the development of each topic there is a constant aim to begin, on the level of the pupil, with the study of concrete cases and to lead by easy steps to as clear and comprehensive an understanding as can be attained in the time usually allotted to the

subject. The point of view throughout is that of the secondary school and not that of the college or university. The attention is directed first and chiefly to the "how" rather than to the "why" of phenomena, thus laying a firm foundation in the well-established facts and principles of the subject, that is, the physics which every intelligent person ought to know. Theories and philosophical discussions have been in general reserved for the more mature mind and the advanced courses.

The mathematical relations between measurable quantities have been recognized throughout, but it has been done without the extended use of mathematical formulas. It is believed that this fixes the attention upon the *physical relations* rather than upon the *forms of expression.* On account of their immaturity of mind beginners in physics commonly obtain from the mathematical formulas little more than short methods of "getting answers" to problems. The plan of treatment aims to develop genuine knowing and to discourage mere "definition learning."

Though from the first the pupil is constantly impressed with the usefulness of physics and with the fact that its mastery greatly increases his power in dealing with his environment, the book is not burdened with what may be called cyclopedic information. The field of applied physics is as broad and diversified as the field of human activity, hence beginners can take only a glimpse of it here and there. What parts shall be selected from this universe of material must be determined chiefly by the teacher, who is acquainted with the local conditions and the special needs of the pupils. Information is valuable, yet the cultivation of the scientific spirit and the development of the ability to acquire and to express knowledge accurately are of still greater value to the student, whether he is looking forward to life in the college or out of it. The good student or the good workman is the one who thinks and finds expression for his thoughts, and not the one who is merely informed. The text furnishes ample material for a secondary school course; yet it will be noted that the number of topics discussed is somewhat less than that usually offered for

the first year. In case special time conditions require a further shortening of the course, it can be done by omitting the sections in smaller type.

The general subject of Mechanics has been treated in a most direct and concrete manner with the expectation that the pupil will be able to secure a good foundation in this important but generally troublesome topic.

The treatment of Heat is unusually full of principles and their applications. The relative importance of this subject, in its relations both to the life of the pupil and to his work in other sciences, justifies this plan. The discussion of Sound, the least important of all the subdivisions, is much shorter than that usually given, yet it offers all that is of any considerable value to people generally.

From the experimental point of view the interest value of the topic of Light is of the highest, yet in the extent of its practical value it cannot compare with either Mechanics or Heat. It is believed that the use of *waves* and *wave fronts* instead of *rays* will develop an increased interest in the explanations of the phenomena of light.

Magnetism and Electricity are treated as extensively and accurately as the time will permit. An exhaustive treatment of any of the phases of these subjects is not claimed nor is it desired.

In addition to the general points already mentioned, it is confidently believed that the reader will find an especially marked improvement in the treatment of the following topics: Fluid Pressure, Force, Energy, Work, Machines, Waves, and the Formation of Images.

The cuts have been prepared with reference to their teaching value rather than their entertaining value, hence photographs and pictures of apparatus are rarely used.

It is hoped that the time and thought spent upon the questions and problems may make them more than ordinarily useful. They are intended both to furnish a review and to show the application of the principles set forth in the text. The first questions

in any group are usually so simple that every pupil who has acquired a fair understanding of the text will be able to answer them. For the benefit of the exceptionally strong pupils a few problems of a rather difficult nature are sometimes introduced and placed at the end of the list. Throughout, emphasis has been laid upon the physical rather than the mathematical side of the problems.

While containing many features that are believed to be a decided advance over prevailing practice, there is no attempt to use revolutionary methods. It is confidently believed that the treatment conforms to well-established pedagogical principles. The choice and scope of the subject-matter, and the general arrangement of the topics of this text-book, accord with the recommendatians of the leading associations of Physics Teachers, and with the requirements of the College Entrance Examination Board.

Finally, this book has been prepared in the belief that there is a demand for a *text-book* "pure and simple"; a book that does not attempt to do the work of either the teacher or the laboratory, one which aims to present only those phases of the secondary school course in physics which the pupil should acquire from the study of a book. The work in physics in the secondary schools is steadily improving, and radical departures from present methods would not be wise. This book is offered with the hope that it may lighten the burden of the teachers and the pupils and that it may prove another step toward higher ideals, better methods, and deeper interest.

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CONTENTS

TEXT-BOOK IN PHYSICS

I. INTRODUCTORY

1. **Scope and Aims of Physics.** — The study of physics is the study of a department of nature. An exact statement of the scope and content of physics is difficult to give and cannot be fully appreciated by the beginner. It is very desirable, however, that the student, at the conclusion of a course, should have a clear conception of the work he has been doing and of the accompanying results. To this end it is highly important that from the beginning both teacher and pupil have definite aims. The chief aims may be briefly stated as follows:

1. To secure an exact and systematic apprehension of a reasonable number of the facts of physical science.
2. To produce in the pupil's mind a clear grasp of the relations of these facts to one another and to other departments of knowledge.
3. To secure an accurate expression of the knowledge thus gained.
4. To develop the desire and the power to investigate.
5. To show the application of physics to the arts, other sciences, and the affairs of life generally.

In striving to attain the ends here stated there is need of a teacher, a laboratory, and a text-book. To dispense with any of these means will, to a great extent, diminish the value of the results secured. The student must realize that the study of this or other books alone is in no true sense the study of physics, and that book work furnishes but a part of the excellent training offered by this subject.

Common experience and experiment, under the guidance of the teacher, must furnish the elementary facts and ideas.

The text-book is intended to help the student to formulate, to arrange, and to classify the knowledge thus gained and to determine the correct meaning of the experiments and demonstrations. In addition, books give much valuable information, which on account of lack of time and facilities could not be directly secured by the student.

Meaning of Terms

2. **Experience.** — Many of the most important facts of life are discovered by our daily observation, begun in infancy. With most people this method of getting knowledge is undirected and its results are vague and inaccurate. In spite of this, because of frequent repetition, the quantity of information thus gathered is generally large and it constitutes a valuable stock of raw material upon which we must make frequent demands in building our more scientific structure.

3. **Experiment.** — Since common experience is narrow in its field, and frequently too vague in its results, and because it becomes necessary to emphasize or revive an experience, it is often desirable to experiment.

What is an experiment, and how does it differ from common experience?

When a boy fills his bicycle tire by means of an air pump, his common observation of the process affords experience only. When he uses the same air pump on the same tire to discover whether he can burst the tire or not, he is experimenting.

Driving a nail with a hammer when making a box is not an experiment, but driving the nail with the same hammer for the purpose of finding out how much it is driven by each blow is an experiment.

Thus we see that the fundamental difference between common observation and an experiment consists in the *attitude of*

mind of the observer. An experiment consists in bringing about certain conditions and observing the results *in order that knowledge may be gained.* Hence the student who arranges his materials according to the directions of a book or a teacher and does not observe and try to interpret the results is not experimenting; he is only toying with apparatus. Nor does similar work by the teacher, in the presence of a class, properly constitute experimenting if the student gets from it nothing but interesting entertainment.

4. **Theories; Laws; Principles.** — Our final attempts to interpret and to explain the facts of experience and experiment are summed up in comparatively brief concise statements variously called *theories, laws,* and *principles.*

Any doctrine which has been advanced for the purpose of explanation and has found general acceptance, yet is still open to a reasonable doubt, may be called a *theory.* In many instances theories are helpful to the giving of a correct understanding, but the student must not forget the element of doubt in them, and whenever it is possible to give a sufficient explanation without their use, he had better not use them.

Whenever a larger knowledge has removed the element of doubt from a theory, or when from the very beginning we feel confident that a general statement is proved beyond a reasonable doubt, we call it a *law* or *principle.* The distinction between a law and a principle is not sharply drawn.

Since laws and principles are accepted as true, any of the changes or phenomena of nature are considered explained when they have been shown to come under a particular principle or law.

5. **Example and Illustration.** — In teaching any subject it is frequently desirable to use examples and illustrations.

An example is a sample or specimen of the particular thing under discussion. Thus an *example* of buoyancy is shown when a stone is suspended in water.

An illustration, however, is not a sample of the matter under discussion, but something else which, on account of one or more points of resemblance, is able to throw light upon the other. Thus if a stone is suspended from a spring balance and a student pushes downward on it with one hand and upward twice as much with the other, we have an *illustration* of buoyancy. This comparison throws light upon the manner in which water pushes upward and downward upon bodies immersed in it. It is not, however, an example of buoyancy.

MEASUREMENT

6. **Units.** — Our attempts to determine how much there is of anything are called measuring. A large number of different kinds of things may be measured, the most common of which are length, surface, volume or capacity, weight, money or wealth, and time.

A distinction may be made between *direct* and *indirect* measurements. For the purpose of direct measurement we must first select a certain amount of the same kind of thing as that which is to be measured and then find how many times this selected quantity is contained in the one to be measured. That quantity of a given kind selected for the purpose of measuring other quantities of the same kind is called a *unit*. Thus to measure length directly, we must select a length — for example, the length of this page — as our unit of length, and, to measure surface directly, we may take the surface of the page as our unit of surface or area. If we now find, by applying the page to a table, how many times the page length is contained in the table length, and how many times the page surface is contained in the table surface, we have then directly measured the length and surface of the table in our own *arbitrary* units. When we wish to compare our measurements with those of other people, the disadvantages of arbitrary units become obvious.

In many instances, instead of applying the concrete unit directly it is much more convenient to measure at first, not the quantity which we wish to know, but some other or others, and by a known relation between these different quantities, compute or calculate the number of units in the desired quantity. A quantity which is determined in this way is said to be measured *indirectly*. This indirect method is more convenient in some cases, such as the measuring of surfaces and volumes, but in many other cases, such as the measuring of heat and electricity, it is the only possible method. For example, it is generally more convenient to find the number of square inches in a sheet of paper by measuring its length and breadth and from these computing its area, than it is to apply a body having one square inch of surface to the paper directly, and so find by counting how many times its area is contained in that of the paper.

Systems of Measurement

7. **Standard Units.** — The need of fixed and legalized units of the commonest kind of quantities, such as length, weight, and value, or money, was recognized early in the history of the race. Units established by the authority of governments or by international agreement are called standard units. Unfortunately, the fundamental or most commonly used standard units are not the same in all the great countries.

8. **The Metric System.** — Because it is strictly a decimal system and on account of the simple relation existing between the units of length, volume, and weight, the best of all the systems of standard units now in use is that, established by the French government in 1799, familiarly known as the Metric System. We shall consider only that portion of this system which is directly useful in elementary physics.

Length. — The unit of length in this system is the shortest distance between the ends of a certain bar of platinum, kept in Paris, when at a temperature of 0° C. (freezing point). This

length, called a meter (m.), is equivalent to 1.09 yards, or 39.37 inches.

Following the same plan as that used in establishing our United States units of money, the meter was subdivided into 10 equal parts called decimeters, that is, tenths of meters; these again into 10 equal parts called centimeters (cm.), hundredths of meters; and these again into 10 equal parts called millimeters (mm.), thousandths of meters. Of these smaller units the one most commonly used is the centimeter (cm.), equivalent to .3937 inch (1 inch = 2.54 cm.).

Surface. — As a unit of surface or area the most convenient is the area of a square which has a unit length for each of its two sides. This method of choice gives us as many surface units as we have linear units, but for most scientific work the square centimeter (sq. cm.) is taken as the unit of area. It must be noted that the term *square centimeter* as a unit of surface refers to the quantity of surface or area, and not to its shape; hence a square centimeter of area may be a square, a circle, or any other figure (Fig. 1).

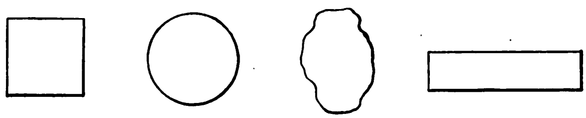

FIG. 1. — The first figure is 1 cm. square. Each figure has an area of 1 sq. cm.

Volume. — Though any volume might be chosen as a unit volume, for obvious reasons the simplest is the volume of a cube, or a body which has the same unit of length for each of its three different dimensions. In this way we get the cubic meter, cubic centimeter, cubic foot, and cubic inch. In the study of elementary physics the commonest unit of volume is the cubic centimeter (c.c.), though for the measurement of liquids and gases the cubic decimeter (1000 c.c.) called the liter, is sometimes used (Fig. 2).

Here, too, it must be understood that a body having a volume

of 1 c.c. may be in the form of a cube, but also it may be a sphere or have any other form or shape (Fig. 3).

Mass. — The unit of mass that is most commonly used in the metric system is the amount of matter equivalent to one thousandth part of a certain piece of platinum (also kept in Paris), known as the standard kilogram (k.). This mass, called the gram (gm.), is practically the same as the quantity of matter represented by a cubic centimeter of pure water at 4° C. (39° F.).

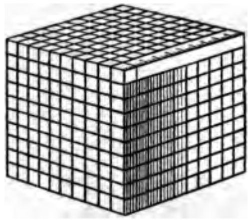

FIG. 2. — The relation between the cu. cm. and liter. 1000 c.c. = 1 cu. decimeter = 1 liter.

In addition to the gram the other most important metric units of mass are the kilogram (1000 gm.), and the $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$ parts of the gram called respectively the decigram, centigram, and milligram, but generally written as decimal parts of the gram. The kilogram is equivalent to 2.2 lb. For other equivalents see the following table:

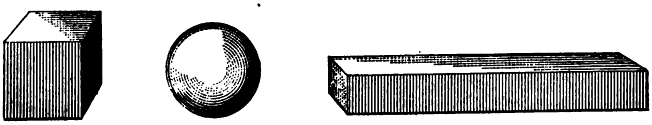

FIG. 3. — The three bodies have the same volume but different shapes. The volume is 1 c.c.

APPROXIMATE EQUIVALENTS

METRIC TO ENGLISH		ENGLISH TO METRIC	
1 mm.	= 0.3937 in.	1 inch	= 2.54 cm.
1 cm.	= 3.937 in.	1 foot	= 30.48 cm.
1 meter	= 39.37 in.	1 yard	= 0.914 meter
1 kilometer	= 0.621 mile	1 mile	= 1.609 kilometers
1 sq. cm.	= 0.155 sq. in.	1 sq. in.	= 6.45 sq. cm.
1 cu. cm.	= 0.061 cu. in.	1 cu. in.	= 16.39 c.c.
1 liter	= 1.057 quarts	1 pint	= 0.473 liter
1 gram	= 15.43 grains	1 oz.	= 28.35 gm.
1 kilogram	= 2.20 lb.	1 lb.	= 0.454 kilogram

9. **The Relation between a Gram Mass and a Gram Weight; Masses Proportional to Weights.** — The attraction of the earth for a gram mass is called a gram weight. Evidently the word *gram* when used without qualification may refer to either a mass or a weight. It is frequently necessary to state definitely which is meant, though the conditions under which it is used will often tell which meaning is intended. The gram as a unit of mass has the same value all over the earth, but because the earth's attraction varies with certain changes of location the weight of the gram mass, that is, a gram weight, is not necessarily the same at two different places, though we believe it is always the same at a given place. From this it follows that at any one place (1) equal masses have equal weights, and (2) any two different masses bear the same ratio to each other that their weights sustain to one another; that is, the *masses of bodies are proportional to their weights.* Hence we may measure masses relatively by finding their weights at the same place.

10. **The Unit of Time.** — The basis of time keeping is found in the yearly and daily motions of the earth. On account of the annual revolution of the earth around the sun the daily rotations of the earth as determined by observations of the sun do not require exactly equal intervals or lengths of time at all seasons of the year. Having found the average or mean solar day, it is divided into 24 equal intervals, hours, and these into 60 minutes, and these again into 60 seconds. For most physical purposes the duration of time represented by the second is the most convenient. Throughout the scientific world the three most commonly used fundamental units, that is, units not based on any others, are the centimeter, the gram, and the second, these units constituting the basis of the familiar *centimeter-gram-second system of units* (c.g.s. system).[1]

[1] Throughout the book whenever differences exist between quantities which differences are too small either to be measured, or to have a bearing on the point under discussion, those quantities are said to be practically the same.

11. The Variation in the Value of Physical Quantities. — Most people know that the temperature and pressure of the air change from day to day, that the speed of a trolley car is generally increasing or decreasing, and that the volume of a piece of iron or other metal changes as it gets warmer or colder. When temperature, pressure, speed, and volume undergo a change in value, they are said to vary. If any kind of quantity undergoes just as much change in any given unit of time as it does in any other equal unit of time, the quantity is said to *vary uniformly*.

For example, if during a certain hour the temperature rises as much in any one second as in any other second, the temperature is said to vary uniformly for the whole hour. If we think over the measurable quantities with which we are familiar, we shall find not only that most of them vary, but also that most of them may change faster at one time than at another. Indeed, the more extended our knowledge of physical quantities becomes, the more we are impressed with the importance of variation and the fact that strictly uniform variation is rarely found.

12. The Relation between the Value of One Kind of Quantity and the Simultaneous Value of Another Kind. *Direct Variation.* — It is always possible to consider the variation of any quantity in relation to what we call the passage of time. It is in this manner that we determine the speed of a horse or a train. In a similar way we can measure the depth of water in a river at a certain hour of each day in the year and determine whether the change or variation of the depth is the same on each day. If this were done, we should probably find that on some days there is an increase, on others a decrease, and on others no change at all in the depth. In short, the depth of the water, though it generally varies *with the time*, does not *vary as the time*.

On the other hand, two quantities are often so related to each other that a variation in one of them is accompanied by such a change in the other that the new values of both may be found by multiplying or dividing their first values by the same number. Either one of two quantities so related is said to vary directly as the other.

If x is the first value of one kind of quantity and y the first value of another kind of quantity which varies directly as x, then ax will be a second value of one quantity and ay the corresponding value of the other. But $\frac{x}{y} = \frac{ax}{ay}$; hence, when any quantity varies directly as another, the quotient obtained by dividing any of the values of the first by the corresponding value of the other is a constant quantity. For example, it is a familiar fact that the quotient obtained by dividing the circumference of any circle by its diameter is a constant quantity, 3.14159, designated by the Greek letter π. We therefore say that the circumference of a circle varies directly as its diameter Many other examples of direct

variation will appear as we continue our study of physics. (See weight pressure, depth, density.)

Inverse Variation. — Other physical quantities are so related to each other that an increase in the value of either is accompanied by a decrease in the value of the other. If the new value of one of the quantities is obtained by multiplying the first value x by any number a, and the corresponding new value of the other quantity is found by dividing the first value of y by the same number a, then x varies inversely as y.

From this it follows that $x : ax = \frac{y}{a} : y$, or $x \times y = ax \times \frac{y}{a}$.

In general, when any quantity varies inversely as another, the product obtained by multiplying any value of the one quantity by the corresponding value of the other is a constant. One of the best examples of an inverse variation is that which exists between the *volume* of a gas and the *pressure* upon it. (See Boyle's law, page 64.)

13. **The Graphical Expression of Quantities.** *The Graph.* — The different values of any variable quantity can be represented by a set of straight lines, the length of each corresponding to a particular value found by measurement. This is a familiar and effective method of presenting to the mind, through the eye, the relations existing between the successive values of any quantity or the simultaneous values of quantities of the same kind. Geographical and other statistics are often presented by this graphical method.

In addition to this, when considering the variation in the values of two related quantities we may express any two simultaneous values of the two by representing each value by a straight line drawn at right angles to the other. For example, we may represent the successive depths of water at any place in a river by a set of vertical lines drawn from a common base line, and the length of time in days by a set of horizontal lines drawn from a common base line on which the time is counted.

Thus in Figure 4 points a, b, c, d, etc., represent the depth measured vertically from the base line x and also the time measured horizontally from the base line y. But a physical quantity, such as the depth of water, cannot change by leaps or steps as does the price of butter and eggs, for in passing from one value a to another value b, it must pass through all the other values between a and b. If, then, we draw a line connecting all the points a, b, c, d, etc., which were located by means of the measurements, this line will represent not only the depths actually measured, but it also approximately represents the depths at all other times between the first and last measurement.

This curved line a, b, c, d, etc., is known as the graph of the depth. In a similar manner from simultaneous measurements we may construct a graph which shows the relation at any time between any two related quantities. It is plain from an examination of Figure 4 that the more

frequently the measurements are made, the more nearly will the graph represent the true relations existing between the quantities at all times. The value of the graph is to be found chiefly in connection with laboratory and other work involving measurements and statistics.

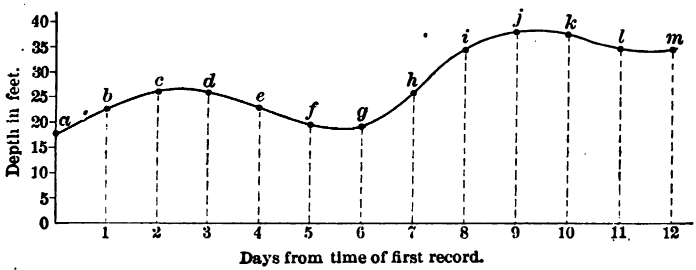

FIG. 4. — Graph showing the relation between the depth of water in a river and the time.

QUESTIONS AND PROBLEMS

1. Give two methods of finding the capacity of a water tank, one of which is an example of a direct and the other of an indirect method of measuring the volume.

2. Convert 3 m. to millimeters, 35 mm. to meters, 48 m. to centimeters. 10 in. is equivalent to how many centimeters? 25 cm. is equivalent to how many inches?

3. Convert 12 k. to pounds. How many grams are equivalent to 1 oz.?

4. A body is moving with a speed of 980 cm. per second; express the speed in feet per second.

5. The height of a tree increases with its age; is it correct to say that the height varies directly as its age? What does the second statement mean?

6. Take the temperature, at the same hour, daily for a week and make a graph showing its variation.

II. MATTER

14. **The Meaning of the Term "Matter."** — For the purposes of elementary physics, common experience has furnished us with a sufficiently exact meaning of the term *matter*. To say that " matter is that which occupies space " or " matter is the receptacle of energy " or " the permanent possibility of sensation," adds little if anything to our common understanding of the term. It is sufficient for our purpose if the student is able to distinguish between that which is and that which is not matter.

Any limited portion of matter to which we may direct our attention is called a *body*. In this sense, then, we may consider an entire steam engine as one body, or when it suits our convenience we speak of any wheel or rivet in the entire structure as a distinct body.

The kind of matter is usually indicated by the term *substance*. Thus water, air, wood, iron, etc., are different kinds of matter, different substances. Whenever a substance undergoes such a change that we cannot afterward recognize it as the same, we conclude that a new substance has been formed, and we call the process a chemical change. The burning of wood, the rusting of iron, the action of an acid on metals, are examples of chemical changes.

15. **Properties of Matter.** — The conduct or behavior of matter when subjected to various tests and the different conditions attending the use of materials has led us to infer the existence in matter of certain characteristics or properties, and to the adoption of certain useful terms to designate them.

Some of these characteristics, because they are always found

in all kinds of matter, are called *general* or essential properties. Thus all bodies have *extension.*

On the other hand, there are many other characteristics which are noticeable only in some kinds of matter, or only when the material is subjected to certain change of conditions, like heating and cooling. These are known as *special* properties. Thus ordinarily glass is brittle and hard, but while being heated to redness these special properties gradually disappear and others are developed.

16. **Terms Applicable to All Matter.** *Impenetrable.* — When a stone is dropped into a tumbler entirely full of water, some of the water overflows; a portion of the water has been displaced by the stone. If the volume of the stone is one cubic inch, exactly one cubic inch of water is displaced, though it may not all overflow, showing that the water and the stone cannot both occupy any portion of the same space at a given time. A study of all substances in similar ways has led to the general conclusion that no two portions of matter can ever actually occupy the same space at any given time. The term *impenetrability* is used to express briefly this fact concerning matter. The apparent contradictions to the statement that impenetrability is a general property of matter readily disappear when we recognize that in no instance is the space which a body seems to occupy completely filled by it. Driving a nail into wood, dissolving salt in water, etc., consist in putting the material of the nail or salt between the parts or particles of the wood or of the water.

Extension. — All bodies have extension in three directions, commonly called length, breadth, and thickness. These are really only three lengths in three directions at right angles to each other. The absence of any one of these three dimensions is sufficient to prove that the thing under consideration is not matter. Hence geometrical points, lines, and surfaces are not bodies in the physical sense.

Volume. — The space which any body occupies is called its *volume.* Bulk, size, and cubical content are sometimes used with the same meaning. Though the *volume* of any object may be selected as a unit with which to measure the volume of other bodies, we rarely use any but standard units of volume, such as the cubic inch (cu. in.), cubic foot (cu. ft.), cubic centimeter (c.c.), cubic meter (cu. m.), etc.

17. **Mass.** — An examination of a common thermometer shows that the mercury has been sealed within the tube by melting the glass; hence none of the liquid can escape. If we heat or cool the mercury, its volume becomes larger or smaller, but the quantity of mercury is neither increased nor decreased. We can express this fact briefly by saying that the *mass* of the mercury is not changed by the heating or cooling.

The *quantity of matter* in a body is briefly called its *mass.* Since in common speech the word *massive* often means large in size, the student is warned against confusing mass with volume or size. If we completely inclose a definite mass of any kind of matter, and then subject it to any known process, whether constructive, like growth, or destructive, like burning, we find that the mass within the inclosure is neither increased nor decreased. This general truth is known as the *conservation of mass.* It is sometimes called the *indestructibility* of matter. Hence we believe that the total quantity of matter in the universe is neither increased nor decreased by any of the changes which occur in nature. Houses, bridges, books, may be created and destroyed as such, for they each require a special form and kind of matter as well as a definite mass. Their forms may be changed indefinitely, but their masses cannot be changed without adding other matter to the original or removing some from them. Similarly, the growth of plants and animals consists not in the creation of matter, or mass, but only in transforming matter which already exists into new shapes and formations. Such processes as decay and burning likewise consist merely in

a readjustment of the masses already existing into new and sometimes invisible forms, all of which taken together equal the original mass. Standard units of mass are the kilogram, gram, and the pound. The attraction of the earth for any mass is called the weight of that mass, and it usually has the same name as the unit mass. (See sec. 9.)

18. Density and its Relation to Mass and Volume. — Equal volumes, say one cubic centimeter each, of lead and wood when placed on the opposite pans of a pair of scales will not balance. Since at any place equal masses have equal weights, there is plainly more mass in the lead than in the wood, though they are equal in volume. The matter is more concentrated in the lead. We express this fact by saying that lead is denser than wood: But every portion of matter has both mass and volume, either of which may be changed. For example, if the mercury in the thermometer is warmed, it expands, or increases in *volume*, but the mass remains unchanged. The same mass being distributed throughout a larger volume, the mercury is less dense after expansion than before (Fig. 5). When a bicycle tire seems full it is possible to put in a great deal more air, thus considerably increasing the *mass* without appreciably changing the volume. Here the mass increases, but the volume does not; hence the air becomes denser (Fig. 6). A mason dressing a stone changes *both* the *mass* and the *volume* of the stone. In this case the density is unchanged, for both mass and volume change at the same rate. Provided the volume of a body does not change, its density increases as its mass increases. When the mass of a body does not change, its density decreases as its

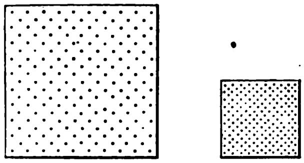

FIG. 5. — Equal masses in unequal volumes. The body with the smaller volume is denser.

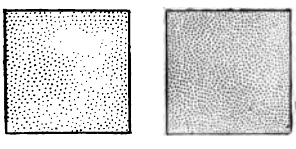

FIG 6. — Equal volumes containing unequal masses.

volume increases. More briefly: the density of a body varies directly as its mass and inversely as its volume.

$$\text{density varies as } \frac{\text{mass}}{\text{volume}}.$$

From this it follows that the density of any substance x bears the same relation to the density of another substance y as $\frac{\text{mass } x}{\text{vol. } x}$ bears to $\frac{\text{mass } y}{\text{vol. } y}$, or

$$\text{dens. } x : \text{dens. } y :: \frac{\text{mass}}{\text{vol.}}\, x : \frac{\text{mass}}{\text{vol.}}\, y.$$

If x and y have equal volumes, then:

$$\text{dens. } x : \text{dens. } y :: \text{mass } x : \text{mass } y.$$

But when the masses are equal, then:

$$\text{dens. } x : \text{dens. } y :: \frac{1}{\text{vol. } x} : \frac{1}{\text{vol. } y}, \text{ or}$$

$$\text{dens. } x : \text{dens. } y :: \text{vol. } y : \text{vol. } x.$$

These discussions show:

(1) The densities of two substances, having equal volumes, are directly proportional to their masses, or to their weights, when both bodies are weighed at the same place.

(2) The densities of two substances, having equal masses, are inversely proportional to their volumes.

The density of any substance is expressed by stating the number of units of mass contained in a unit volume. Thus, the density of water is 1 gram per cubic centimeter (at 4° C.), or 62.4+ pounds per cubic foot.

Much confusion arises from the use of the terms "heavier" and "lighter" as the equivalents of denser and less dense. One object may be heavier than another and yet both may have the same density.

TABLE

SHOWING THE AVERAGE DENSITY OF SOME COMMON SUBSTANCES AT ORDINARY TEMPERATURES

SUBSTANCE	EXPRESSED IN GM. PER C.C.	EXPRESSED IN LB. PER CU. FT.
Aluminum .	2.6	165.
Copper . . .	8.8	555.
Gold	19.3	1205.
Iron (cast) .	7.4	456.
Lead	11.3	708.
Mercury . . .	13.596	848.
Oak	0.75	46.
Alcohol . . .	0.79	49.
Water	1.00 (4° C.)	62.4
Air	.001293	0.08+

QUESTIONS AND PROBLEMS

1. What two things must be known in order to compute the density of a body?
2. If the body is a block of wood, how will you find the two necessary quantities? If it is a liquid, how will you find them?
3. Which of these is a *direct* measurement? Which are indirect?
4. State the density of water, first using metric units, then using English units.
5. What is the weight of 1 liter of water? of 45 c.c. of water?
6. Why is it wrong to say that 1 c.c. = 1 gm.?
7. If 60 c.c. of wood weigh 32 gm., state the density of the wood.
8. What is the distinction between a kilogram mass and a kilogram weight? Which may change with a change of location? Why?
9. Since the term *mass* does not mean the same as the term *weight*, on what principle can the weight of a body be used in finding its density?
10. A piece of metal 5 cm. thick, 6 cm. wide, and 7 cm. long weighs 1638 gm. Find its density.
11. The density of mercury is 13.6 gm. per cubic centimeter; what weight of mercury is required to fill 12 c.c.? What is the weight of 1 liter of mercury? What is the volume of 1 k. of it?
12. A tank 2 ft. high, 3 ft. wide, and 4 ft. long will hold what volume of water? what weight of water? what weight of mercury?

19. States of Matter. — There are three well-defined conditions of matter called the solid, the liquid, and the gaseous states. Many substances may be found in any one of these

states. Water, for example, may exist as ice (solid), water (liquid), and vapor or steam (gaseous). A mere addition or removal of heat, in sufficient quantity, may change water and many other substances from any one of these states into another. Some substances, for example, paper and wood, cannot be changed to a liquid or gaseous state, because they undergo a change in structure, a chemical change, when highly heated, thereby forming two or more new substances. Thus, wood when heated to a high temperature forms a number of substances, some solid, some liquid, and some gaseous, that can no longer be called wood.

FIG. 7. — The less dense hydrogen diffuses downward and the denser oxygen upward until they are thoroughly mixed.

A more extended discussion of the special features of solids, liquids, and gases will be given under separate topics. It is sufficient here to notice only the distinguishing features of each state.

Solids exhibit a considerable permanence of *form and volume.* Their parts maintain their relative position, and unless the bodies are very large, their entire weight may be supported by a horizontal surface alone without producing any considerable change in their shape. In some cases it is extremely difficult to decide whether to call a substance a solid or a liquid, since it seems to have some of the characteristics of each.

FIG. 8. — The denser acid at *S* diffuses upward and changes the color of the blue litmus at *L*.

Molasses candy and some kinds of wax at certain temperatures are familiar examples of such bodies.

Fluids, comprising both liquids and gases, yield readily to any action which tends to change their shape or form. They cannot be supported by a level surface alone, for when placed on such a surface they

flow or spread horizontally, hence the supporting body or vessel must have sides.

Liquids maintain a practically definite volume, and upon being transferred from a smaller to a larger vessel change their shape alone. In a vessel of larger volume than their own they flow to the lowest parts and establish a free upper surface, hence a top is not required to keep them in the vessel.

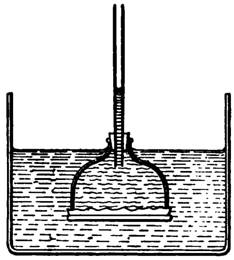

FIG. 9. — The outside liquid diffuses through the porous membrane faster than the other liquid does.

Gases, on the other hand, readily undergo a change in volume as well as shape. A given mass of gas transferred from a vessel of smaller to one of larger volume immediately expands and uniformly fills all the space offered to it. To keep the volume of a gas constant it must be surrounded on all sides. Hence gases have no free surface. Putting corks into bottles containing alcohol, ether, and other liquids is necessary to prevent the gas or vapor and not the liquid form of these substances from escaping at the top by evaporation.

FIG. 10. — The illuminating gas in the outer jar diffuses through the porous jar faster than the air diffuses outward; hence the air bubbles appear below.

20. Diffusion. — A layer of alcohol placed in a jar on top of a quantity of water and left for a number of hours gradually mingles with the water beneath until there is finally a uniform mixture. Alcohol is less dense than water, and being above the water the mixing is not due to its weight. Many other liquids when similarly arranged will also slowly mix. Still others, such as kerosene and water, will remain in contact indefinitely without mixing appreciably.

Any two gases, for example, hydrogen and oxygen, when placed as shown in Figure 7, with the less dense above, will

in a few minutes become thoroughly mixed and so remain. The mixing of any liquids or of any gases in the manner shown, that is, when the denser of the two fluids is beneath the other, is called *diffusion* (Fig. 8).

Diffusion also takes place when the liquids or the gases are separated by such substances as unglazed or porous earthenware and animal membranes. In the latter case the process is commonly called *osmose* (Figs. 9 and 10).

Diffusion is probably due to *molecular motion* (see next section).

21. **Kinetic Theory of Matter.** — In attempting to explain the facts shown by such familiar processes as expansion, contraction, evaporation, the mixing of liquids and gases by diffusion, as well as those shown by the characteristic differences between solids, liquids, and gases, scientists have been led to the adoption of a system of belief known as the *kinetic theory of matter.* According to this theory all matter is made up of exceedingly small constantly moving particles called *molecules.* It is further believed that these molecules require space in which to move, or vibrate, in addition to that actually occupied by their own mass; hence, generally speaking, molecules are not in contact, though there are probably frequent collisions and reboundings.

The differences between solids, liquids, and gases may then be explained by assuming a difference in the freedom of motion of the molecules. In solids the molecules can vibrate, but they must maintain their relative position, like galley slaves chained to their seats. In liquids there is some freedom of motion, as shown by the process of diffusion, but though the vibratory motion may be considerable, the onward motion is slow like that of a person making his way through a dense crowd. Hence liquids diffuse slowly. In gases the freedom of motion is nearly perfect, each molecule having little or no vibratory motion, but moving onward until its motion is reversed or changed in direction by

collisions with its neighbors or the walls of the containing vessel, the motion being much like that of a swarm of bees in a large closed room.

This theory explains why gases increase their volume to the limit of the space offered them and why they diffuse so rapidly.

The relation of the kinetic theory to the processes of evaporation and expansion will be discussed in connection with the general subject Heat.

As regards the actual size of molecules little is known. They are so extremely small that in our efforts to imagine them we could get little help from figures even if they were definite. The smallest particle visible by the most powerful microscope contains countless millions of molecules.

Terms Applicable to Matter of Certain Kinds and Conditions

22. **"Special Properties."** — A large number of terms are commonly used to designate the different characteristics of matter. This is partly because the number of kinds of substances is very large and also because most substances undergo such decided changes in their properties when their temperatures are changed. While it is very probable that the characteristics of matter and the changes in them are dependent upon the nature of the molecules and the action of the molecules upon each other, so little is actually known that so-called explanations of these properties are of little value for our purpose.

In the treatment which follows, it is assumed that the pupil has become well acquainted, through common observation and experiment, with the behavior of at least the common metals and other familiar substances under ordinary conditions and when they are subjected to changes of temperature and pressure, and to such other tests as would show the value of these materials for various practical uses. Instead of giving mean-

ingless definitions of these so-called properties, the text aims to help the student to make the proper choice of terms in his effort to name or designate these properties when they come under his notice. They are all everyday terms of frequent use.

Compressible; Porous. — If the volume of any substance is carefully measured and the substance is then subjected to greatly increased pressure, the volume will be found to be less; hence matter is said to be compressible. All gases are highly compressible. (See section 19.)

Liquids, on the other hand, require so much pressure to produce even a slight change in their volume that for most purposes we may neglect the small change in their density which is produced by the pressures to which they are commonly subjected.

Solids, excepting those which, like wood, cork, blotting paper, contain microscopically visible spaces between their parts, are likewise very difficult to compress. The compressibility of substances is an evidence of the existence of intermolecular spaces or pores. In gases at the ordinary pressure and density these pores must be very large.

Elastic. — A wooden ball dropped upon the table rebounds. When we push upon a bicycle tire the air within yields to the pressure, but it returns to its original volume when the pressure is removed. Flat stones when thrown nearly parallel to the surface of water rebound again and again before they finally sink. If we extend our investigations, we shall find that all bodies, whether solids, liquids, or gases, when reduced in volume by addition of pressure, regain or partly regain their original volume when this added pressure has been removed, hence all bodies are elastic though in widely varying degrees. In the examples quoted the elasticity is shown by *a change in volume.*

Many solids, also, show elasticity by *a change in shape,* but liquids and gases show no disposition to return to their original shape after a change has been made.

If we slightly bend a bar of lead, it will regain its form when

released, but after a greater bending it remains bent. It has passed its *elastic limit*. A piece of soft wood placed between the jaws of a vise may be diminished to half its volume. When released it expands, but usually does not nearly return to the original volume. Here, too, the elastic limit has been passed. Liquids and gases, though very unequally compressible, have no elastic limit. This means that no amount of compression can permanently change their volume. They always return *perfectly* to their original volume when the original pressure is restored. *Within the limit of its elasticity, the greater the displacement a body undergoes the greater is the restitution force or pressure which the body exerts.* This is known as Hooke's law. An example is found in the common spring balance where a displacement of the pointer of 2 in. indicates twice the pull required to produce a displacement of 1 in. from the zero of the scale.

Malleable. — Many solids such as lead, some kinds of iron, gold, silver, etc., when struck heavy blows will flatten or spread permanently without breaking. Substances behaving in this way are said to be *malleable.*

Ordinary cast iron is *very slightly* malleable, but wrought iron is highly so, hence it may be used for rivets even when cold. Most substances become more malleable when they are heated. Glass and wrought iron when red hot are nearly as malleable as putty or wet clay. The most malleable of all metals is gold, which can be hammered into sheets called gold leaf, so thin that about three hundred thousand of them are necessary to make a layer one inch thick.

Ductile. — When a piece of moderately warm molasses candy is pulled at both ends it readily elongates, at the same time becoming thinner. Iron wire is made from malleable iron by first rolling, practically hammering, the red-hot bars into rods about the diameter of a lead pencil. These rods are then drawn longer and thinner at the ordinary temperature. Any solid which will thus permit of being permanently elongated, at the

same time becoming thinner, is said to be ductile. The most malleable are generally the most ductile substances. Red-hot glass is very ductile.

Plastic. — Many solids may be readily molded into any desired shapes by a comparatively small pressure. Putty, wet clay, dough, molasses candy, are familiar examples. Such solids are said to be plastic.

Brittle. — The behavior of a piece of ice or cold glass when struck a blow is in sharp contrast with the conduct of the malleable and plastic substances. Because these and many other solids break, when thus struck, without undergoing a permanent change of form, they are said to be brittle.

Hard and soft are relative terms. There is no definite standard for either. We can easily tell which of two bodies is harder by rubbing them together and seeing which is scratched or which is scratched more. The one that shows the greater effect is softer. In this way mineralogists have fixed upon an arbitrary scale of relative hardness.

Solution. — If common salt, in not too large quantities, is mixed with water, it dissolves or passes into a condition called a solution. When the water is evaporated the salt is left behind in a solid state.

Other liquids will dissolve other solids, but no one liquid will dissolve all kinds. Changing the temperature usually changes the amount of the solid dissolved by a given weight of a liquid.

Crystallization. — Many substances when passing into the solid state, either by slowly cooling the liquid form of the substance or by a gradual evaporation of its solution, assume certain definite geometrical structures, bounded by plane surfaces; such solids are said to be crystalline. Snowflakes, frost, rock candy, and granulated sugar are familiar examples of crystalline substances. Crystallization and solution find their full treatment in chemistry and mineralogy.

Cohesion; Adhesion. — When we try to break a piece of crayon, we are conscious of an attraction between its parts. The attraction between those particles or molecules of a body which are next to each other is called cohesion. In *solids* this attraction is great enough to prevent the molecules from changing their relative position. Hence cohesion gives to solids their permanence of form and furnishes what we commonly call their strength. In *liquids* the cohesion is much less than in most solids, yet the molecules in a drop of water hanging from one's finger attract each other enough to support the weight of the drop unless it finally becomes so large that the weight exceeds the cohesion. The distance between the molecules determines to a great extent the amount of the cohesion, hence two portions of the same material, for example, two pieces of clean lead, may frequently be reunited by pressing them close together. If we first soften the substances to be united, as the blacksmith does, they cohere more readily, for it is then possible to bring more of the molecules near to each other.

When the surfaces in contact are those of two different kinds of material, for example, paint and wood, or glue and paper, the molecular attraction is frequently called *adhesion.* Any distinction between the terms *cohesion* and *adhesion,* though frequently convenient, is of minor importance.

In *gases* the molecules are so far apart that there is practically no cohesion between them. On account of the small cohesion in liquids and the lack of it in gases all fluids must be moved by a push or pressure from behind; they cannot be pulled or drawn through a tube or pipe, though when in a very small tube they may be held or retarded, to a great extent, by their adhesion to its walls.

Tenacity; Tensile Strength. — If rods or wires of different solids, all having the same area of cross section, are subjected to a pull or tension, as shown in Figure 11, it is found that they sustain very different loads without breaking. The great-

est load supported in this way, per unit cross section, is a measure of the *tenacity* or *tensile strength* of the substance. Tenacity is plainly due to the cohesion of the molecules. Solids differ greatly in tenacity, steel, for example, having more than fifty times the tensile strength of lead.

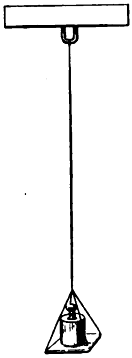

FIG. 11. — The tensile strength of the wire is shown by the load it will carry.

23. **Surface Tension of Liquids.** — If we blow a soap bubble in the familiar way and then remove the pipe from the mouth, the bubble slowly contracts, driving the air out of the pipestem (Fig. 12). When a wire ring supported by a handle and having a string hanging from one side is dipped into a soap solution, a film extends across the circle with the thread lying across it (Fig. 13). When the film is punctured on either side of the thread the unbroken film on the other side contracts and draws the thread away from its former position. If the thread has a loop (L) at the free end and the film is punctured (with a hot wire), the loop will open into a circle (Fig. 14). These and many other facts show that *the surface layer of a liquid acts like a stretched elastic solid;* that is, the surface is constantly trying to contract and become as small as possible. This effort of the surface to contract is known as the *surface tension of liquids.*

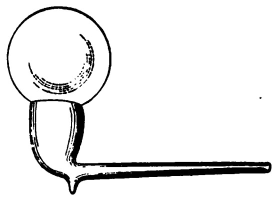

FIG. 12. — The bubble contracts on account of surface tension.

FIG. 13. — An equal surface tension within and without the loop L.

An interesting effect of surface tension is shown by making a mixture of alcohol and water of the same density as olive oil, and then putting into this mixture 1 or 2 c.c. of the oil. No matter what shape the oil may have in the

beginning or what shape may be given to it, the oil when let alone will assume the spherical form, as shown in Figure 15. The surface tension changes the shape of the oil by contracting the surface (not the volume) until there is the smallest possible surface for the given volume. It can be shown mathematically that a given volume of any substance when in the spherical form has less surface than when it is in any other shape. On this account raindrops are spherical, except in so far as they are flattened by the air through which they are falling. Small drops of mercury on the table, and small drops of water on a dusty board, are, in spite of their weight, rendered nearly spherical by surface tension. When the drops become large, or when the liquid has a strong adhesion for the solid, as water has for clean wood, the surface tension is overcome by a greater action (the weight or the adhesion), and the liquid spreads. The floating of a needle and the walking of certain insects on water are familiar effects largely due to surface tension.

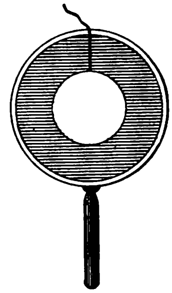

FIG. 14. — The unbroken film without pulls the loop into a circle.

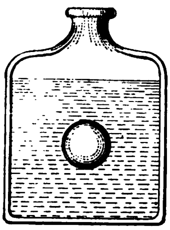

FIG. 15. — On account of surface tension the drop of oil becomes spherical.

24. Relative Adhesion of Solids and Liquids. — When water is put into a clean glass vessel, around the sides of the vessel it rises higher than the general free surface, as shown in Figure 16. This shows that there is less attraction between the adjacent molecules of water than there is between the molecules of water and those of glass. If a little lard or other oily substance is rubbed on the glass, the water does not rise along the sides as before; it does not cling to or wet the lard. Evidently the

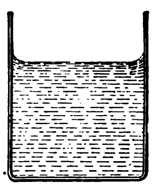

FIG. 16. — The water is curved upward at the edges of the glass.

water molecules attract each other more than they attract those of the lard. When mercury is put into a clean glass dish the mercury is curved downward around the side of the vessel as shown in Figure 17. Mercury does not cling to or wet a clean glass surface. If a strip of zinc is first cleaned with dilute sulphuric acid and then thrust into the mercury as shown in Figure 18, the mercury will rise along its sides, and when the zinc is withdrawn the mercury clings to or wets it.

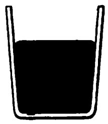
FIG. 17. — The mercury is curved downward at the edges of the glass.

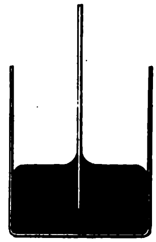
FIG. 18. — The mercury wets the zinc and is curved upward.

From these facts it is easily understood that the curvature of a liquid surface at its point of contact with a solid depends upon both the solid and the liquid used. (The curving of a liquid surface as just described is sometimes called capillary action, though it is not strictly such.)

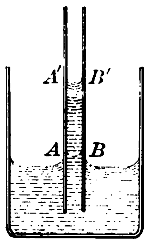

FIG. 19. — The water shows capillary elevation.

25. Capillary Action; Capillarity. — When one end of an open glass tube of large diameter, for example, a lamp chimney, is thrust into a jar of water, the liquid stands at the same level within and without the tube. But when we use another tube of about 1 mm. diameter, the free surface of the water stands higher within the tube than in the jar (Fig. 19). If a similar tube is placed in mercury, the free surface of the mercury stands lower in the tube than it does in the jar (Fig. 20). In both cases the difference between the level of the surface within and that without the tube is produced by what is known as *capillary*

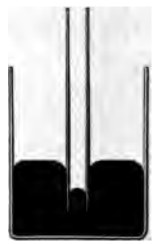
FIG. 20. — The mercury in glass tube shows capillary depression.

action. The rising of the water is an example of *capillary elevation,* the falling of the mercury an example of *capillary depression.*

Though capillary action may easily be noticed in tubes having a diameter as great as a quarter of an inch, the effects are greatest in tubes of very small or hairlike diameter, which are on this account called *capillary tubes.*

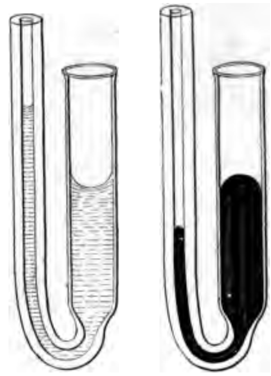

FIG. 21. — Capillary elevation and depression shown by U-tubes.

Both kinds of capillary effects can be shown by a U-tube, one arm of which has a large and the other a very small diameter (Fig. 21). They may also be shown by two glass plates with two of their edges in contact and the opposite two separated by a strip of wood as shown in Figure 22.

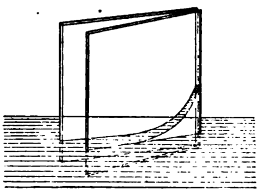

FIG. 22. — The water rises highest where the plates are nearest.

Capillary effects are the result of the joint action of surface tension, the relative adhesion of the liquid for the solid, and the cohesion between the liquid molecules. The contracting action or surface tension of the sharply concave surface of the water in the capillary tube shortens the curve between the sides A and B (Fig. 19), and overcomes the pressure upon the water, hence it rises. At the same time the adhesion of the water for the glass causes it to creep higher along the sides of the tube. These actions continue until the downward pressure of the liquid above AB counterbalances the surface tension at a certain level $A'B'$, and the surface remains curved.

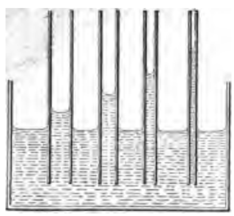

FIG. 23. — The water rises highest when the diameter is least.

When a convex surface is formed, as when the glass tube is placed in mercury, it can be shown by similar reasoning that the effect of contraction lowers the mercury until the opposing weight pressure of the outside liquid balances the surface tension.

Careful experimenting has established the following laws of capillary action:

1. *Liquids rise in capillary tubes when they wet them, and are depressed when they do not wet them* (Figs. 19 and 20).

2. *The amount of elevation or depression varies inversely as the diameter of the tubes used* (Figs. 22 and 23).

3. *The amount of elevation or depression decreases when the temperature of the liquid rises.*

The action of blotting paper, pens, lamp wicks, sponges, towels, etc., are all familiar examples of capillary action.

Capillarity also plays a most important part in the growth of plants and animals, being an important factor in the motion and distribution of water and other liquids through their tissues.

Questions and Problems

1. How could you prove that air is matter?

2. When soda water effervesces a gas comes off; where are the particles or molecules of this gas before the liquid is drawn from the fountain?

3. Prove by examples that you know the proper use of the terms *substance, body, elastic, malleable,* and the other terms used in describing the nature and behavior of matter.

4. When a stick of sealing wax is held in a flame, explain why the melted end becomes rounded.

5. Explain the action of a towel in wiping a wet hand. Why is starch in the towel a hindrance to its action?

6. A book standing on end on a wet shelf frequently becomes wet to the top of the pages. Explain.

III. THE MECHANICS OF LIQUIDS

Pressure

26. Intensity of Pressure and Total Pressure. — A book lying upon one's hand, on account of its weight, acts upon the hand. We may call this action of the book upon the hand a pressure. When a jar is filled with a fluid, for example, water or air, the fluid acts against the bottom as well as all other parts of the jar which it touches. This action of the fluid against the jar is known as the pressure of the fluid. Generally speaking, any body is said to exert pressure when acting upon another in contact with it. Because the term *pressure* implies contact, the attractions and repulsions of magnets are not called pressures so long as there is a distance between the bodies involved. A pressure is a force, hence it may be measured in pounds, grams, dynes, or any other units of force.

Pressure may be thought of and expressed in two ways: First, we may consider alone the number of pounds or grams with which the body acts on the whole of any surface of contact. This gives us what is called the *total pressure.* Thus if a block of wood weighs 400 gm., its total pressure upon a table on which it is resting is 400 gm. Second, we may, by first finding both the area of the surface of contact and the total force, compute the *number of units of force per unit of surface.* Pressure when thus expressed we call *intensity of pressure* or *pressure intensity.* Thus if the block of wood weighing 400 gm. has a surface of contact of 50 cm.^{2}, the pressure, if uniform, will be 8 gm. per square centimeter. The unqualified term *pressure* may have either of these two meanings, and when thus used is often confusing to beginners.

The common expression "the pressure of the water on the bottom of the jar" may mean either the total pressure or the pressure per square inch. On this account the student is urged to form the habit of deciding definitely which of these two meanings he intends to express, in any case, and to use the expressions "total pressure" and "intensity of pressure," at least until he becomes thoroughly familiar with their difference, and also in all cases where the unqualified word *pressure* might be misunderstood.

The relation between intensity of pressure and total pressure may be expressed as follows:

pressure intensity $= \dfrac{\text{total pressure}}{\text{area of surface}}$. For example, no. of gm. per cm.$^2 = \dfrac{\text{no. gm.}}{\text{no. cm.}^2}$, and total pressure = area × intensity.

27. **Fluid Pressure.** — Liquids and gases, frequently called fluids, always fit themselves closely to any surface they touch, and their action upon such surface is called fluid pressure. Because the molecules or particles move over each other so easily, a fluid when at rest must always press perpendicularly or normal to the surface of contact, for if it pressed in any other direction it would slip or flow along the surface. For a similar reason the pressure intensity at any one point in any fluid at rest must be the same in all directions or motion would result.

Two Causes of Fluid Pressure. — All fluids have weight, and on this account they all exert a pressure against the containing vessel. In addition to this the air, a piston, or some body, other than the fluid or part of it under consideration, may push or press upon it, thus causing the fluid in turn to press upon everything it touches.

The fluid pressure, produced by the *weight of the fluid* itself, is called *weight or gravity pressure.* The fluid pressure produced by the action of some *body in contact with the fluid* is called

external pressure. The words *external* and *weight* here plainly refer to the origin of the pressure.

28. The External Pressure of Fluids; Pascal's Law. — A piston[1] when thrust against a fluid as shown in Figure 24 produces a pressure in the fluid which we have called *external pressure.* If water is used in such an apparatus, it will be observed that the water comes out of all the openings. The piston presses against the water in *one* direction, *the water transmits the pressure in all directions.* If air or any other gas is used, a like effect is produced, but the bulb must be filled with smoke or surrounded by water to render the motion of the gas visible. In this manner it can be demonstrated that fluids *transmit external pressure in all directions* (Figs. 25 and 26).

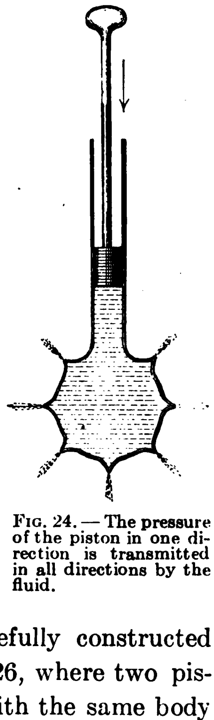

FIG. 24. — The pressure of the piston in one direction is transmitted in all directions by the fluid.

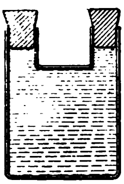

FIG. 25. — A downward pressure on one cork produces an upward pressure of the liquid at the other.

If we fill a two-necked bottle with water, insert two closely fitting corks, then as we drive in one of the corks the other flies out, as shown in Figure 25, or the bottle may even burst. If we use a more carefully constructed apparatus as shown in Figure 26, where two pistons *A* and *B* are in contact with the same body of water, *A* having an area of 1 sq. in. of contact, and *B* 2×2, or 4 sq. in. of contact surface, we find, neglecting the necessary friction, that 1 lb. placed on *A* will

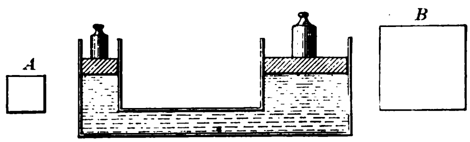

FIG. 26. — The total pressures at *A* and *B* are proportional to the contact surfaces of the pistons.

[1] Any plug or partition which may be easily moved through a tube, yet fitting closely to the sides, may be called a piston.

balance 4 lb. placed on *B*. Because the total pressure at *B* and the area over which it is distributed are both four times as large as at *A*, the pressure per square inch is the same at both pistons. We may change the areas of these pistons and change the forces upon them, or we may use any other fluid instead of water; we find that the pistons always balance when the intensity of pressure is the same at both. Since the pressure at either piston may be considered as transmitted to the other, we conclude that *fluids transmit external pressure without change in the intensity.*

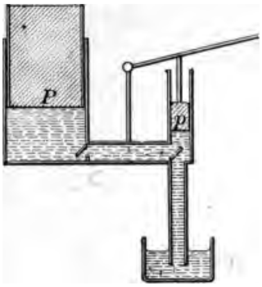

FIG. 27.—Diagram to illustrate the principle of the hydraulic press.

This and the former conclusion may be summed up in the following statement known as Pascal's law:

External pressure is transmitted by fluids in all directions without change in the intensity.

From Pascal's law it follows that when we know or can find the pressure per unit surface exerted by any body *upon* any fluid, we also know the pressure intensity exerted by the fluid, not counting any pressure due to other causes.

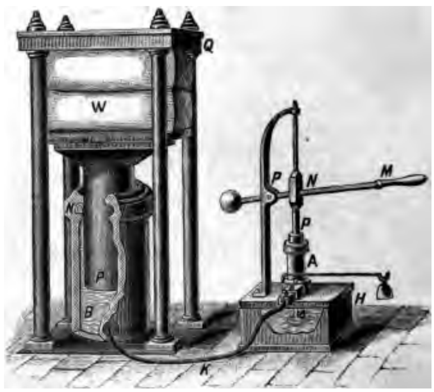

FIG. 28.—A simple form of hydraulic press.

Having found the intensity of an external pressure, the total pressure on any contact surface can be found by multiplying the pressure per unit surface by the whole number of units of surface. Thus if the external pressure on a fluid is

5 lb. per square inch, the total pressure of the fluid on a surface 8 in. × 10 in., or 80 sq. in., will be 80 × 5 lb., or 400 lb.

Some very important applications of Pascal's laws are found in the machines known as the *hydraulic press* and the *hydraulic elevator*. The first of these is shown in principle by Figure 27, but in detail by Figure 28, and the second by Figure 29.

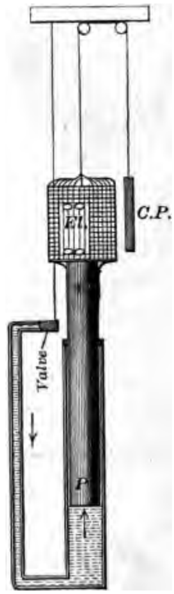

FIG. 29. — The weight of the elevator is nearly counterbalanced by *C.P.* The water is turned on or off by a cord running from the elevator to the valve. The water pressure at *P* lifts the elevator with its load.

QUESTIONS AND PROBLEMS

1. The total pressure of a piston upon a fluid is 64 lb. If the area of contact is 16 sq. in., what is the intensity of pressure at the piston? Is this called "external" or "weight pressure"? Why?

2. The fluid pressure produced by the small piston in a certain hydraulic press is 18 gm. per square centimeter; what is the intensity of the pressure transmitted to the large piston? Find the total pressure on the large piston if the dimensions of the contact surface are 8 cm. and 12 cm.

3. In a certain hydraulic press the total pressure against one piston is to the total against the other as 3 is to; 16 what is the relation between the intensities? What is the relation between the contact areas of the two pistons?

4. Find the contact area of the small piston of the hydraulic press referred to in problem 3, if the total pressure at the large piston is 7200 lb. and its contact area 5 in. by 6 in.; find the intensity of pressure at the small piston.

5. A man exerts a pressure of 40 lb. on the piston or plunger of a bicycle pump. If the surface of the piston in contact with the air has an area of 2.5 sq. in., compute the pressure intensity of the air against the inside of the tire. State the law involved in this problem.

6. In constructing a certain hydraulic elevator the water pressure is 40 lb. per square inch; what must be the area of the piston if the elevator and its load is not to exceed 1 ton? Would the computed pressure move or balance the entire load?

29. The Weight Pressure of Liquids. — All liquids have **weight.** On account of this weight liquids always exert a

pressure upon the vessels containing them and upon everything else that they may touch, as a boat or a stone. The pressure thus produced is called the *weight pressure* (gravity pressure) of the liquid. Since its laws are different, weight pressure must be carefully distinguished from *external pressure,* not only at this time, but in all discussions and problems pertaining to fluid pressure. When both pressures are involved we must discuss and compute them separately. It has been shown that in a liquid *at rest* the pressure intensity at any *one point* must be the same in all directions for an excess of pressure in any direction would set in motion the easily moved molecules.

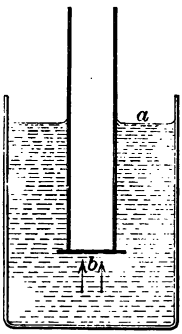

FIG. 30. — The upward pressure of the water at *b* holds the card against the tube.

The familiar fact that water flows from a hole in the bottom of a bucket or other vessel is sufficient evidence that liquids exert a *downward* weight pressure. The *upward* weight pressure within the liquid can be shown by putting a card over the end of a lamp chimney and thrusting it down into water as shown in Figure 30. Water may now be poured into the chimney, and then the downward weight pressure within will become equal to the upward pressure on the card when the depth within the chimney is the same as that without. It follows that the upward pressure intensity at any point is equal to the downward pressure intensity at that and all other points on the same level. When a bottle or jar with holes in the side is filled with water while the holes are closed with the fingers, the water exerts a *lateral* weight pressure against the fingers,

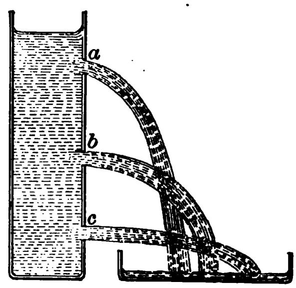

FIG. 31. — The rush of water shows that the pressure is greatest at *c* and least at *a*.

for when they are removed the water comes out as shown in Figure 31. By carefully noting the speed of the issuing streams as indicated by the path of the water, we can easily see that the speed of the water is greatest at the hole which is farthest from the top, or free surface, and further that the speed decreases at all the holes as this free surface[1] of the water becomes lower (Fig. 32). The vertical distance of any point in a liquid from the free surface is called the *depth* at that point. The relative speed of the water at the different openings shows that the lateral pressure is greatest where the depth is greatest, and least where the depth is least.

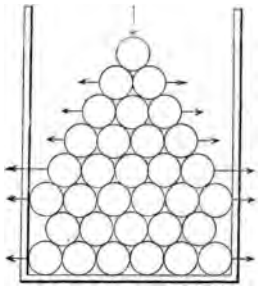

FIG. 32. — Showing how a downward weight pressure becomes lateral.

FIG. 33. — The water presses against the finger.

If we take a bent tube as shown in Figure 33, open at both ends, close the lower end with the finger, fill with water and remove the finger, the rush of water shows that it was pressing laterally against the finger. If we insert three such tubes into the holes of the bottle of Figure 31, making the joints tight by pieces of rubber tubing surrounding the glass, we have the apparatus of Figure 34.

As water or any other liquid is poured into the jar we find it rising in both jar and tubes until we stop pouring. The free surface comes to rest at practically the same level in all the tubes and in the jar, any slight difference being due to capillary action.

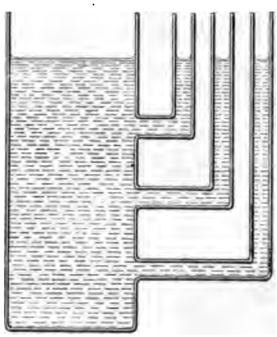

FIG. 34. — The different free surfaces of the same body of liquid are on the same level.

[1] The term *free surface* is used to designate the surface which is exposed to the open air or atmosphere.

This fact is sometimes expressed by the current statement, "Water seeks its level." Since the liquid in each tube, small though it be in volume and weight, can exert enough pressure to prevent the liquid from coming out of the jar at the corresponding opening, it follows that the *weight pressure* of a liquid, though produced *by its weight*, is *not identical with its weight.* We find that there is the same pressure per square inch, or the same pressure intensity, at the depth of any opening whether it is the liquid in the tube pressing inward or the liquid of the same depth in the jar pressing outward.

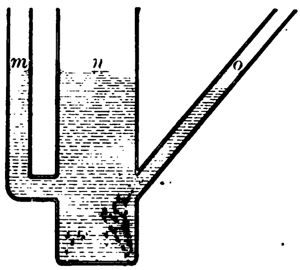

FIG. 35.—Weight pressure depends on the vertical distance from the free surface.

Let us next suppose that the jar has two holes on the same level, and that the tube running through one hole is vertical, while the other is slanting, as shown in Figure 35. Liquid now flows into this slanting tube until the length of the column exceeds that in the vertical tube; but since the pressure in the jar at both holes is the same, this longer slanting column must exert the same pressure as the shorter vertical column exerts, hence in computing weight pressure the *depth of the liquid at any point must be measured vertically from the level of the free surface to the point in question.*

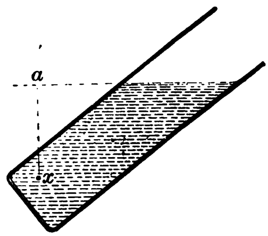

FIG. 36. — The depth of water at x is the vertical distance ax.

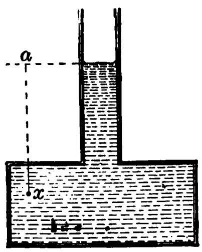

FIG. 37. — The pressure at x is the same as at all other points on the same level. The depth must be taken as ax.

Thus in Figures 36, 37, the depth of the water at the point x is the distance ax, and all points on the same level or horizontal line with x are at the same depth, hence

sustain the same pressure without reference to the quantity of water actually over the points. The truth just demonstrated may be summed up as follows:

The intensity of weight pressure of a liquid varies directly as the vertical depth. For this reason if a U-tube is partly filled with any liquid, the free surfaces in both arms will be at the same level, as shown in Figure 38, and this whether the two arms have the same diameter or not, provided capillary action is neglected.

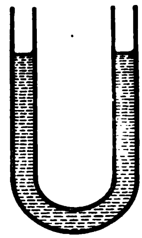

FIG. 38. — The free surface is at the same level in both arms.

30. The Relation of Density to Weight Pressure. — If a quantity of mercury is put into a U-tube and water is afterward poured into one arm only, the water and mercury will come to rest, as shown in Figure 39. From the discussion in the last section it is evident that the mercury below the level *a* in either arm balances that below *a* in the other arm.

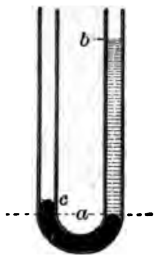

FIG. 39.

If we measure the vertical depth of the entire water column *ab*, and the depth of the mercury column *ac* which balances it, we shall find that the water column is 13.6 times as deep as the mercury column. To produce as great intensity of pressure as the mercury column *ac* produces, the water must be 13.6 times as deep, thus compensating for its smaller density by its greater depth, for the density of mercury is practically 13.6 times that of water. Hence mercury 1 cm. deep exerts a pressure 13.6 times as intense as water 1 cm. deep exerts. Water and kerosene, or any other two liquids that do not mix, may be used instead of water and mercury, as shown in Figure 40. The same reasoning holds, but the ratio between the depths is different. We therefore conclude that the pressure per unit sur-

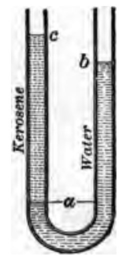

FIG. 40. — The pressure of water having a depth *ab* is equal to that of kerosene having a depth *ac*.

face or *intensity* of weight pressure *varies directly as the density of the liquid used.*

The general principles which have just been shown are summed up in the following laws:

1. *The intensity of weight pressure for a given liquid varies directly as the depth of that liquid, the depth being measured vertically from the level of the free surface.*

2. *The intensity of weight pressure at the same depth of different liquids varies directly as the density of the liquid used.*

It must be noticed that the first law is not strictly true if for any reason the liquid varies in density. But since liquids are *very slightly* compressible, we may neglect any difference in density thus produced for depths not exceeding a few hundred feet, provided the *temperature is uniform.*

31. **How to compute the Weight Pressure of a Liquid.** — Let Figure 41 *a* represent a jar with vertical sides, the bottom of which is 1 ft. square. Suppose water is poured into it until the depth is 1 ft., the volume of the water will then be 1 cu. ft. Since the density of water is about 62.5 lb. per cubic foot, the water will now press upon the bottom of the jar with a force of 62.5 lb. But the area of the bottom is 1 sq. ft., hence the intensity of the weight pressure is here 62.5 lb. per square foot. If the bottom of another vessel is 2 ft. square, or has an area of 4 sq. ft., then when filled to a depth of 1 ft. there will be a total of 4 cu. ft. of water, but by the same kind of reasoning there will still be a pressure of 62.5 lb. per square foot. Hence, *when water is* 1 *ft. deep, the intensity of its weight pressure is* 62.5 *lb. per square*

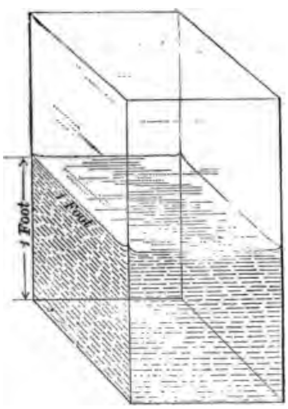

FIG. 41 *a*. — Water 1 foot deep exerts a pressure of about 62.5 lb. per sq. ft.

foot, regardless of the quantity of water or shape of the vessel.

If Figure 41 *b* represents a vessel, the bottom of which has an area of 1 sq. cm., then if the water it contains is 1 cm. deep, its volume is 1 c.c. Since 1 c.c. of water always weighs about 1 gm., the *pressure of water is 1 gm. per square centimeter when water is 1 cm. deep*, without regard to the quantity of water or the shape of the vessel. If the depth of the water in the vessels (Figs. 41 *a* and 41 *b*) were increased, the pressure on the bottom would likewise be increased, for the pressure of the upper cubic feet or cubic centimeters would be transmitted to the bottom of the vessel as well as that of the cubic foot or cubic centimeter in actual contact with the bottom, hence we can find *the pressure intensity for any number of units of depth by multiplying the pressure for a unit depth by the number of units of depth.*

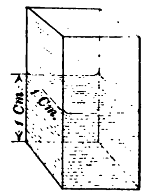

FIG. 41 *b*. — Water 1 cm. deep exerts a pressure of 1 gm. per sq. cm.

For example, water 10 ft. deep will exert a weight pressure of 10 × 62.5 lb. = 625 lb. per square foot, and water 23 cm. deep will exert a pressure of 23 × 1 gm. = 23 gm. per square centimeter.

To compute the weight pressure of any other liquid we must know its density as well as its depth. Since the density of mercury is 13.6 gm. to the cubic centimeter, the *weight pressure of mercury is 13.6 gm. per square centimeter when 1 cm. deep.*

The total weight pressure on the bottom of any vessel can readily be found by multiplying the pressure per unit surface by the number of units of surface.

32. To compute Weight Pressure on the Side of Any Vessel. — Since the pressure at any point in a fluid is the same in all directions, the lateral pressure at any point must be the same as the downward pressure at that point. If we consider a row

of points on the side of the vessel (Fig. 42) from the top to the bottom, the vertical depth of the water at these points will vary from 0 at the free surface to 12 cm. at the bottom or lowest point. Since this depth along the side increases *uniformly*, the average depth will be one half the sum of the extreme depths, or $\frac{1}{2}(0 + 12) = 6$ cm. By similar reasoning, with all the other points in the side we conclude that the *average depth* of the water, which presses against the side, is 6 cm. Consequently the average pressure is 6×1 gm. per square centimeter, or 6 gm. per square centimeter. If the same vessel were filled to the same total depth with *mercury*, the *average depth* of the mercury would likewise be 6 cm., but on account of the greater density of mercury, the average pressure intensity would be 6×13.6 gm. per square centimeter, or 81.6 gm. per square centimeter.

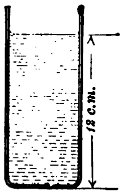

FIG. 42. — The depth along the side increases from 0 at the top to 12 cm. at the bottom.

To find the *total* weight pressure against the side, we first find the *pressure per unit* surface at the average depth, and then multiply the result obtained by the *number of units of surface.*

Thus water in a tank 10 ft. deep, 5 ft. wide, and 8 ft. long will exert a total pressure on the bottom of 625 lb. (intensity) $\times$ 40 (number square feet in bottom) = 25,000 (pounds total pressure).

On one end of the tank, which has an area of $10 \times 5 = 50$ sq. ft., the total pressure will be 312.5 lb. (average intensity) $\times 50 = 15{,}625$ lb. (total pressure).

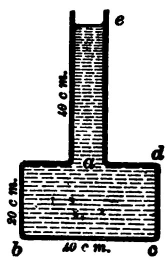

FIG. 43.

Let Figure 43 represent a box 20 cm. high, 20 cm. wide, and 40 cm. long, with a tube projecting 40 cm. above the level of *a*. If the box alone contains water, it will have an average depth of $(0 + 20) = 10$ cm. along the side *dc*, and the pressure intensity

will average only 10 gm. per square centimeter; hence the total pressure against side *dbc* will be 10 (average intensity) $\times$ 800 = 8000 gm. But when box and tube are both filled with water, the total pressure on the bottom or any side may be found by exactly the same method. Let us consider the pressure which is now upon the side *dbc*.

The depth of water at *a* is 40 cm. and at the bottom it is 60 cm.; hence the average depth on the side *dbc* is $\frac{1}{2}$ (40 + 60) = 50 cm. The average pressure intensity on the side is then 50 times what it is when water is 1 cm. deep, hence 50 gm. per square centimeter. The total pressure against this side will then be 50 gm. (intensity) $\times$ 800 (area) = 40,000 gm. This is an excellent example of the general fact that the weight pressure of a liquid is *not the same as the weight* and that a very small weight of liquid like that contained in the tube may exert a very great pressure.

The Free Surface of a Liquid at Rest is Level. — If the water in a jar is disturbed by shaking so that it assumes the position shown in Figure 44, it cannot remain in this position, for the depths at points x, y, z on the same level are not the same, consequently there will be a greater weight pressure from z toward y and x than from x toward y and z. On account of this unbalanced pressure water will begin to move from the place of greater to the place of less pressure. When it finally comes to rest, the pressures at these points must be equal, and equal depths of water will then be over x, y, and z. A large free liquid surface is not a true plane, for it has the curvature of the earth. This curvature is so slight that the surface of a small body of water at rest is practically plane or flat, except as already mentioned in connection with capillary action.

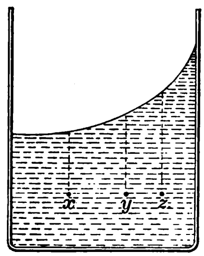

FIG. 44. — The vertical depths at x, y, and z are different, hence, the water flows from z toward x.

33. Applications of the Principles of Weight Pressure. — A city water works (Fig. 45), with its reservoir and system of

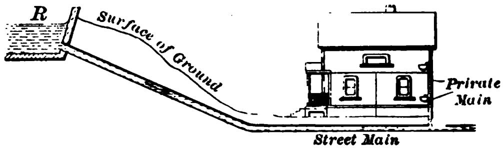

FIG. 45. — The source of the water R must be higher than the highest outlet in the house.

distributing pipes, the water gauge on a steam boiler (Fig. 46), artesian wells, natural springs (Fig. 47), canals with their locks and gates, the spirit level (Fig. 48), are some of the many instances in everyday life in which the principles of weight pressure of liquids are involved. It must be noted, however, that when a fluid begins to move, as in a system of water pipes, the laws which have been determined for a liquid at rest are no longer strictly appli-

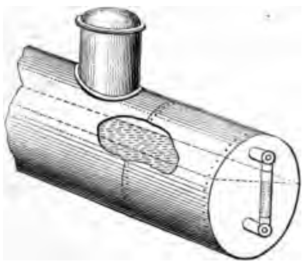

FIG. 46. — Water gauge on a steam boiler.

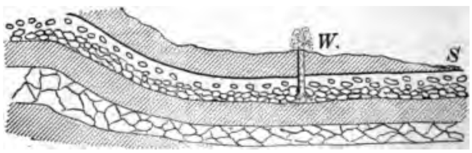

FIG. 47. — The water entering the porous stratum at the highest point flows out at the artesian well W or the natural spring S.

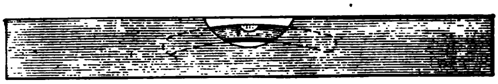

FIG. 48. — The bubble of air in the glass tube is always at the highest point, hence is at the middle when the bar of wood is level.

cable. For example, the water will not rise so high in any building as the free surface in the reservoir when the flow

in any part of the building or in the main pipe near by is a large part of the full capacity of the pipe. An experiment

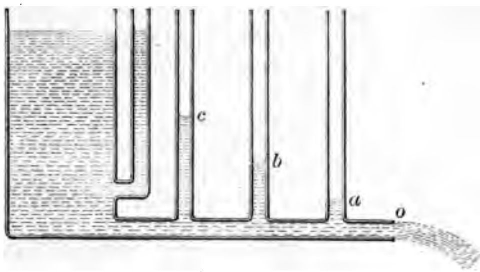

FIG. 49. — When water flows freely at *o* the pressure falls most at *a* nearest the outlet.

with the apparatus shown in Figure 49 demonstrates this point.

PROBLEMS AND QUESTIONS

1. Upon what two things does the intensity of weight pressure depend? Find the intensity of pressure when water is 1 ft. deep; 20 ft. deep; 1 cm. deep; 18 cm. deep.

2. Find the pressure intensity when mercury is 1 cm. deep; when 7 cm. deep; when kerosene is 1 cm. deep; when kerosene is 4 cm. deep.

3. Under what circumstances must we use an average depth in calculating pressure? Find the average depth of the water which presses against a side of a cubical vessel 40 cm. high. What is the average pressure intensity? If the same vessel is filled with mercury, find the average depth and average pressure intensity.

4. Compute the total weight pressure on the bottom of a vessel 12 cm. high, 14 cm. wide, and 16 cm. long (*a*) when filled with water; (*b*) when filled with mercury.

5. Make a drawing of the vessel and compute the total weight pressure against any side when filled (*a*) with water, (*b*) with mercury.

6. The gate of a canal lock is 20 ft. wide, and the water level is 10 ft. higher on one side of the gate than on the other. Find how much the total pressure on one side of the gate exceeds that on the other.

7. Would a change in the liquid used in the hydraulic press make any change in the pressure, total or intensity, supposing (*a*) that the pistons are on the same level, (*b*) that the large piston is at a lower level than the small piston? Give your reasons.

8. A rectangular vessel, (Fig. 50.) has a tube attached to the side. The height of the vessel *ab* is 16 cm., the width *ad* is 10 cm., and the other dimension *ae* is 8 cm: If the vessel and tube are filled with water to the level of the surface *aefd*, find the total weight pressure against the bottom, one of the sides, and the top of the vessel.

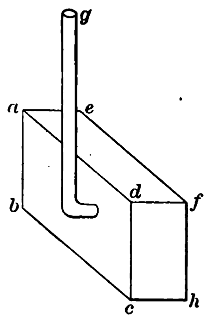

Fig. 50.

9. If the vessel and tube are filled to the level *g*, 20 cm. above the level *aefd*, find (*a*) the average depth of the water which presses against the side *abcd*, (*b*) the total pressure against *abcd*.

10. How would an increase in the diameter of the tube, (Fig. 50.) affect the answers to question 9? If kerosene were substituted for water, how would the answers be affected? Why?

11. If the bottoms of vessels *A*, *B*, *C*, *D*, *E*, and *F* (Fig. 51.) all have the same area, 100 cm.², and the depth of water is 12 cm. in each vessel, state (*a*) the pressure intensity at the bottom of each vessel, (*b*) the total pressure at the bottom of each, (*c*) the vessel in which the total weight pressure on the bottom is equal to the weight of the water, (*d*) the vessels in which the total weight pressure on the bottom is less than the weight of the water, and (*e*) the vessels in which the total pressure on the bottom is greater than the weight of water they contain.

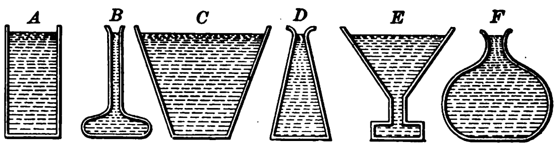

Fig. 51.

12. A house is supplied with water by a reservoir (Fig. 45). What must you know in order to compute the pressure intensity in a pipe in the cellar? in a pipe on the second floor? Will your answers apply when the water is running? Why?

13. What is the meaning of the term *head*, as applied to a water supply? (See dictionary.)

14. The pressure at the bottom of a reservoir is five times what it is at a depth of 4.5 ft. Find the total depth of water in the reservoir.

IV. The Mechanics of Gases and Liquids

34. The Special Characteristics of Gases. — When a bicycle tire is being pumped up there comes no particular instant when we can say the tire is full and will hold no more. For some time after it is fully distended we can continue putting in more air. We test it by pressing upon it, and decide when to stop entirely by the reaction or back pressure of the air within. If we hold the valve open, the air rushes out for some time before we notice any change in the size of the tire. If the inner ball or bladder of a foot ball is partly inflated, then tightly closed and placed under the bell jar of an air pump (Fig. 52.), the air within the ball gradually expands, as the pump removes the air from the jar around the ball, until the ball prevents further expansion. As the air is readmitted to the jar the football returns to its original condition, the air within being reduced to its former volume. These and similar facts relative to air and other gases show that any gas will expand to an indefinitely large volume when the pressure upon it is correspondingly reduced, and, on the other hand, its volume will be indefinitely diminished as the pressure is correspondingly increased. These characteristics, which are common to all gases, are briefly stated as follows: —

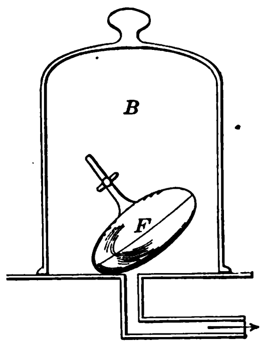

Fig. 52. — The air in F expands as the pressure upon it is decreased.

1. *Gases are very compressible and expansible.*

2. *Gases expand indefinitely, as the pressure upon them is decreased, and they always completely fill any space offered to them, not including the space between the molecules.*

3. *Gases constantly exert a pressure or tension against **all the** walls, including the top, of the containing vessel.*

The pressure of a gas, sometimes called "elastic force," has nearly the same intensity at all points throughout the vessel. That is, on account of the small density of gases, their weight pressure is usually too small to be taken into account. For example, the density of air being less than $\frac{1}{700}$ as great as the density of water, in a vessel of air 100 cm. deep, the weight pressure is less than $\frac{1}{7}$ of a gram per square centimeter.

It is interesting to note that if water or any other liquid were substituted for air in our experiments with the bicycle tire or the football, we should find it impossible to produce any perceptible change in its volume by such changes in pressure as we could produce with the pumps, liquids are so nearly incompressible. The characteristics of gases, as above shown, may be explained by the kinetic theory of matter.

35. **Kinetic Theory of Gases.** — As already stated, it is believed that the molecules of every gas are in constant motion, flying back and forth in all directions, occasionally striking each other, but many of them continuously bombarding the walls of the containing vessel and thus producing the pressure of the gas upon the walls. Heating the gas increases the molecular motion, hence increases the pressure of the gas against the inside of the containing vessel.

36. **Meaning of the Term "Atmosphere."** — The entire earth or material world is composed of solids, liquids, and gases. The gaseous portion or envelope which surrounds the solid and liquid portions of the earth is called the *atmosphere.*

Any part of the atmosphere, particularly when it is inclosed in some vessel, is commonly called air. A study of the composition of air shows that it really is not a single gas, but a mixture of a number of substances the most abundant of which are nitrogen, oxygen, argon, water vapor, and carbon dioxide. The study of the nature of these substances and of the part

they take in many of the processes of life and manufacture properly belongs to the science of chemistry.

The Density or Weight of a Unit Volume of Air — Air being a form of matter, is attracted by the earth; *that is, air has weight.* The density of air is easily changed by changing its temperature and the pressure upon it. Careful experimenting has determined that 1000 c.c. 1 liter of pure air weighs 1.29 + gm. at the standard pressure (see Sec. 38) and at the freezing point of water.

37. Atmospheric Pressure. — Though the density of air is very small, yet on account of its great depth (probably 50 miles or more) the atmosphere, like all other fluids, exerts a weight pressure upon the solid and liquid portions of the earth beneath and also upon all bodies immersed in it. There are many easy ways of demonstrating this pressure. Thus if a tumbler is filled with water, covered with a card, and inverted, the atmospheric pressure keeps the water in the tumbler.

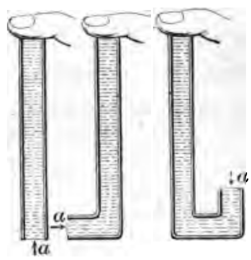

FIG. 53. — Showing atmospheric pressure in three directions.

If tubes of small diameter open at both ends, shaped as shown in Figure 53, are thrust into a jar of water and one end closed with the finger after they are filled, they may be removed from the jar and yet remain full. The atmospheric pressure keeps the water from coming out. These experiments likewise show that atmospheric pressure is exerted in all directions. In all these cases the weight pressure of the water is counterbalanced by the pressure of the atmosphere. We can prove the existence of atmospheric pressure by means of other liquids. Mercury, for example, is particularly well suited for this purpose. On account of its very great density a very small depth of mercury is sufficient to produce a great pressure intensity. All those effects, which are commonly attributed to "suction,"

are really produced by atmospheric pressure. Some of them will be studied later in connection with the pump and siphon. (See Secs. 48–52.)

Since the weight pressure of any fluid depends upon both its depth and density, it follows that the depth of the atmosphere must be very great in order to produce the existing pressure with so small a density (.00129 gm. per cubic centimeter). The exact depth of the atmosphere is unknown, and its density varies so much with a change of elevation, on account of the great compressibility of air, as well as on account of its great inequality of temperature, that we cannot compute atmospheric pressure, as we do the weight pressure of a liquid, from its depth and its density. Hence atmospheric pressure must be measured indirectly by counterbalancing it with the weight pressure of a liquid.

Questions and Problems

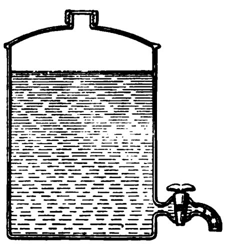

Fig. 54. — A kerosene can.

1. Why is air not well suited for use in the hydraulic press?

2. Why must the cap on the top of a kerosene can (Fig. 54) be opened in order to have a free flow of oil at the tap? It will sometimes flow intermittently with a gurgling sound without removing the cap; explain.

3. Explain why the ink does not overflow and how the supply is maintained at O in the inkwell shown by Figure 55.

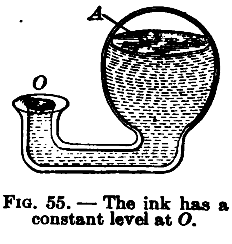

Fig. 55. — The ink has a constant level at O.

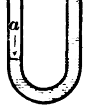

Fig. 56.

4. Is the pressure of the air within, next to the finger, greater or less than the atmospheric pressure (Figs. 56 and 57)? Answer a similar question relative to Figure 58.

5. Assuming that the liquid is water and the difference between the levels of a and b (Fig. 56) is 10 cm., find how much the one pressure exceeds the other. Find the excess pressure for the same difference in levels when mercury is used.

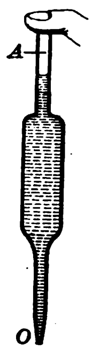

FIG. 57. — A pipette. Convenient for measuring or transferring small quantities of liquid.

6. Explain the relation of the atmosphere to (*a*) the action of a filler for a fountain pen (Fig. 57), (*b*) the process of "sucking" soda through a straw.

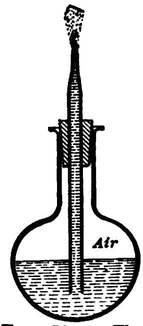

FIG. 58. — The air in the vessel drives out some of the water.

7. Explain the relation of atmospheric pressure to the physical process called breathing.

8. The water rises in vessel *B* (Fig. 59) after the paper has ceased burning. Is the pressure greater at *A* or *B*? How much greater if the level of the water in the tumbler is 6 cm. higher than outside?

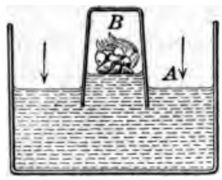

FIG. 59. — A little tissue paper has been burnt in vessel *B*.

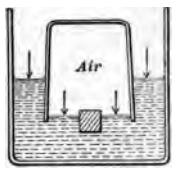

FIG. 60. — The principle of the diving bell.

9. Why does the volume of the air in the inverted tumbler (Fig. 60) become less as the tumbler is thrust more deeply into the water?

10. Explain the starting and stopping of the flow of water in the pipette (Fig. 57) when the finger is removed from and replaced on the top of the tube.

38. How Atmospheric Pressure is Measured. *The Barometer.* — If a glass tube, closed at one end and not less than 34 in. long, is filled with mercury to displace the air, closed with the finger, then inverted, and placed with the open end in a dish of mercury, as shown in Figure 61, the mercury within the tube will come to rest with the top of the column (*b*) about 30 in., or 76 cm., above the free surface (*a*) of the mercury in the dish. This is the celebrated experiment by which Torricelli, in 1643, first

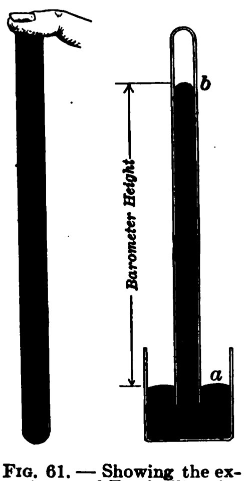

FIG. 61. — Showing the experiment of Torricelli; also the simplest form of barometer.

prove the existence of the atmospheric pressure. The apparatus as thus used constitutes the simplest form of the barometer, an instrument for measuring atmospheric pressure. When great care is taken in filling and inverting the tube, the space above the mercury column contains no air, and is practically an empty space or vacuum. Because mercury evaporates slightly, there is a very little mercury vapor pressing upon the top of the column, but at ordinary temperatures this vapor pressure is so small that it may be neglected.

Let us now consider how the barometer measures pressure. The atmospheric pressure on the mercury in the dish balances, hence is equal to the weight pressure of that part of the mercury column in the tube which is above the level of the free surface (a); for if the top of the tube is opened, the mercury comes to the same level within and without the tube. To find the atmospheric pressure per square inch or square centimeter, it is only necessary to compute the weight pressure of the counterbalancing mercury column. Since we know the density of mercury, and can readily measure the vertical depth of this mercury column (ab), known as the "barometric height," we can calculate, by the method already given, the pressure intensity exerted by the counterbalancing mercury; hence, with this instrument, we may find the atmospheric pressure. For example, when the distance ab is 75 cm., the atmospheric pressure is 75×13.6 gm. per square centimeter = 1020 gm. per square centimeter.

The average atmospheric pressure at the sea level being about equal to that of a column of mercury 76 cm. deep, this has been selected by scientific men as the *standard barometric height or pressure.* In England and America, 30 in. is sometimes used as the standard barometer. The intensity of atmospheric pressure when the barometric height is 76 cm. is found by the ordinary method of calculating weight pressure (Sec. 31). $76 \times 13.59 +$ gm. per square centimeter = 1033 gm. per square

centimeter. This pressure is frequently called one "atmosphere." It must be borne in mind that it is always the intensity of the atmospheric pressure and not the total pressure that is measured by the barometer.

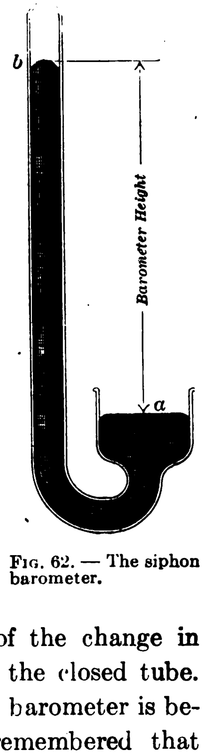

Fig. 62. — The siphon barometer.

Another form of the barometer nearly as simple as the Torricellian form is the U-tube form shown in Figure 62. The long arm of the tube is first entirely filled with mercury, and after the tube has been inverted and placed in a vertical position, the atmosphere acts upon the mercury in the open arm, as shown in the drawing. Plainly a fall of the mercury in the closed column will be accompanied by a rise in the other tube, but by making the diameter of the open tube relatively large most of the change in level will take place within the closed tube. But when the height of the barometer is being measured it must be remembered that the surface exposed to the air changes in level, as well as the other, and that the difference in level is the true barometric height. Hence in the improved forms of mercurial barometer there is an adjusting screw attached, which rests against the leather bottom of the mercury reservoir. By means of this screw the free surface of the mercury can be brought to a constant level before a reading is taken (Fig. 63).

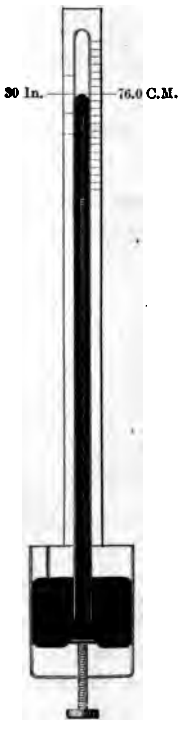

Fig. 63. — The plan of a standard barometer.

Though the height of the barometer is not really the pressure of the atmosphere, the changes in barometric height are proportional to the changes in the pressure. Since many of the uses of the barometer require only the *relative pressures* at different times and places, it is evident that for such purposes barometric heights alone are sufficient. The extensive records of the weather bureau give the atmospheric pressures entirely in terms of barometric heights.

FIG. 64. — Aneroid barometer.

Liquids other than mercury, for example, kerosene, could be used in the construction of a barometer, but because of the small density of most liquids an inconveniently long tube would be required.

A form of barometer, called the *aneroid*, is frequently used (Fig. 64). This form indicates the change in pressure by the rising and falling of the central portion of the lid of an empty air-tight box as the outside atmospheric pressure changes (Fig. 65). The motion of the lid is communicated by a set of levers and wheel work to a pointer that travels over a dial. The instrument is graduated by comparing it with the mercurial barometer. Its special advantages are its portability and extreme sensitiveness.

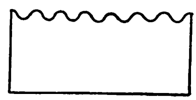
FIG. 65. — The box of an aneroid barometer.

Uses of the Barometer. — The direct use of the barometer is to determine actual or relative atmospheric pressures. But since the atmospheric pressure, like other weight pressures, changes with a change of elevation, we may use this change in pressure to indicate the elevation or a change in the elevation above the sea. Unless corrections are carefully made, this indirect use of the barometer gives results that are only approximately true; for, as has been stated, the atmospheric pressure does not change uniformly as

we ascend, nor is it always the same at a given elevation (Fig. 66). Roughly speaking, an ascent of 900 ft. produces a barometer fall from 30 to 29 in., or an ascent of 120 m. fall from 76 to 75 cm. on the barometer. The changes in the atmospheric pressure which occur from time to time at a given place are associated with other atmospheric or weather conditions in a fairly constant manner. Long and careful observations have established the following general conclusions: —

1. A steadily falling barometer indicates the coming of stormy weather.

2. A steadily rising barometer indicates clearing weather.

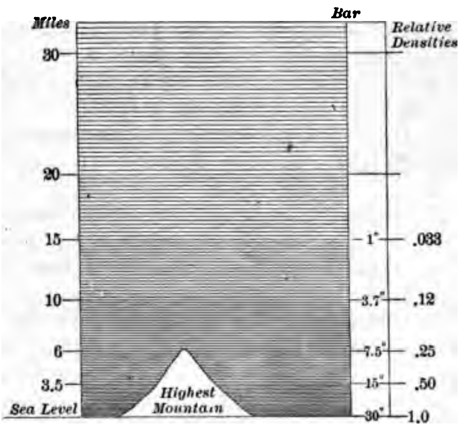

FIG. 66. — Showing the relation between elevation, atmospheric pressure and the density of air.

It must be clearly understood that the barometer is a pressure gauge and not a weather gauge; hence conclusions concerning the weather drawn from its readings are open to the uncertainty which attaches to inferences generally. If barometric readings are taken at the same time over a wide area, such as the United States and Canada, and these records studied in connection with the direction of the wind, the temperature and the humidity, valuable conclusions may be drawn concerning the progress of storms. These conclusions find their expression in the forecasts of the weather bureau.

Generally speaking, the clear cold weather of winter is accompanied by a relatively high atmospheric pressure, while warm waves are usually associated with a low barometer.

Questions and Problems

1. What is the intensity of pressure exerted by a mercury column when it is 1 cm. deep? when it is 20 cm. deep? when it is 76 cm. deep?

2. Compute the atmospheric pressure when the barometric height is 76 cm. Is your answer a total or an intensity of pressure? What else would have to be known to compute the total atmospheric pressure?

3. Prove from principles already established that the diameter of the barometer tube has no effect upon the barometric height, provided capillary action is neglected. In a mercury barometer will capillary action make the actual reading higher or lower than the true reading? In a water barometer?

4. If water were used in the construction of a barometer, what would be the height of a water barometer when the mercurial stands at 30 in.? at 25 in.?

5. Compute the pressure per square inch when the barometer stands at 30 in.

6. If the atmospheric pressure is 980 gm. per square centimeter, what is the height of the barometer?

7. How deep a layer of mercury over the earth's surface would produce as much pressure as the standard atmosphere? How deep a layer of water would produce the same pressure?

8. The density of air is .001293 gm. per cubic centimeter at the earth's surface. Find how high the atmosphere would extend if it were the same density throughout.

9. Explain the principle involved in using the barometer to measure elevations. Give two reasons why the method may give errors in the conclusions.

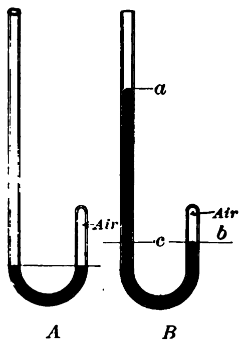

Fig. 67. — The air in the closed arm is fixed in mass but decreases in volume as the pressure increases.

39. The Relation between the Volume of a Gas and the Pressure upon it. *Boyle's (or Mariotte's) Law.* — If a given mass of air is inclosed by mercury in the short arm of a tube, as shown in Figure 67, *A*, with the mercury at the same level in both arms, then the pressure of the inclosed air is equal to that of the atmosphere in the open tube. When more mercury is put into the tube, no air being allowed to enter or escape

from the closed arm, the level of the mercury will then be higher in the open than in the closed arm, as shown in Figure 67, *B*. In this case the inclosed air exerts a greater pressure upon the mercury at *b* than the open atmosphere exerts at *a*. The air in the closed arm balances the atmospheric pressure and that of the mercury column *ac*. By a series of measurements upon the volume and pressure of air in such an apparatus, Sir Robert Boyle first proved that the *volume* of the inclosed air *decreased* at the same rate that the *pressure upon it increased,* provided the temperature was not changed. By experimenting upon other gases the following law, known as Boyle's Law in English-speaking countries, or Mariotte's, in other countries, was determined: *The volume of a given mass of any gas varies inversely as the pressure upon it, provided the temperature remains constant.*

Since the density of a substance varies directly as its mass and inversely as its volume, or density $= \frac{\text{mass}}{\text{volume}}$, it follows that any change in the volume, provided the mass is constant, produces the inverse change in the density. Hence, *the density of a gas at constant temperature increases directly as the pressure upon it.* Very exact measurements have shown that gases do not exactly obey Boyle's Law, but for practical purposes the results obtained by its use may be considered correct, except when the gas is about to pass into the liquid state.

Pressure Gauges. — When the two surfaces of a given liquid stand at the same level in a U-tube, we conclude that the pressures upon these surfaces are equal, but when one surface is at a lower level, as in Figure 68, we conclude that the pressures are unequal, and that the greater pressure is upon the lower surface.

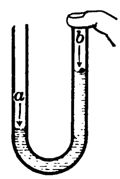

FIG. 68.

On this principle certain instruments called pressure gauges, or manometers, are constructed. There are two common types of such gauges. One is simply the U-tube with both arms open, the other is a U-tube with one

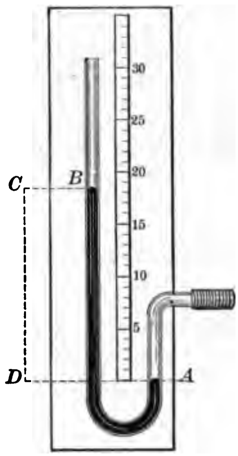

FIG. 69. — The open manometer.

arm closed. In the open-arm gauge (Fig. 69), one of the surfaces of the liquid, generally mercury, is always exposed to the atmosphere at B. Hence CD indicates the difference between the atmospheric pressure and the pressure of the gas in the closed vessel. In the closed-arm gauge (Fig. 70) the closed arm commonly contains mercury only, hence the difference in level serves to measure the pressure in the vessel to which the gauge is attached, provided it is less than the atmospheric pressure. Another form, with air in the closed arm, acts just like the Boyle's law tube already discussed (Fig. 67).

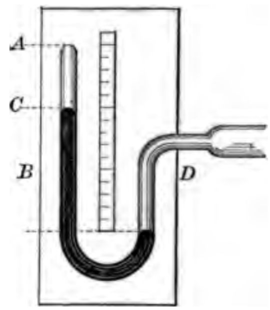

FIG. 70. — Since AC contains no air, the pressure in D is equal to the pressure of the mercury in B which is above the level of the mercury in D.

QUESTIONS AND PROBLEMS

1. A bubble of air in water at a depth of 480 cm. is under what water pressure? If the barometer stands at 70 cm., compute the pressure on the bubble due to both the atmosphere and the water.

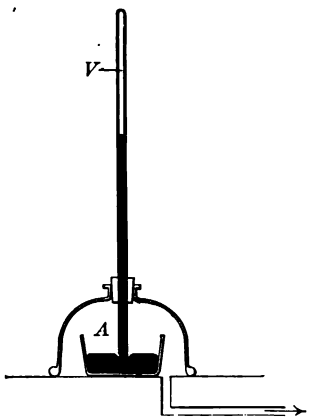

FIG. 71. — The mercury column of the barometer falls when air is pumped out of vessel A.

2. If the volume of an air bubble is 12 c.c. at a depth of 10 m., find its volume when it comes to the surface, the atmospheric pressure being standard.

3. Air is pumped from a vessel, A (Fig. 71), until the surface of the mercury in the tube is only 9 cm. above that in the dish; find the pressure of the air remaining if the atmospheric pressure is 72 cm. What portion of the original air was removed from A?

4. If a vessel is attached to an open-arm manometer, what is the difference between the levels in the mercury

columns when the excess pressure at A (Fig. 69) is 200 gms. per sq. cm.?

5. State the physical reason why air goes into and out of the lungs in the breathing of animals.

6. Explain the transfer of water (Fig. 72), from A to O, as the air is being pumped out of the jar B.

7. What part of the air remains in A (Fig. 71) after the mercury has fallen one fourth of the distance from V to the level of the mercury in A?

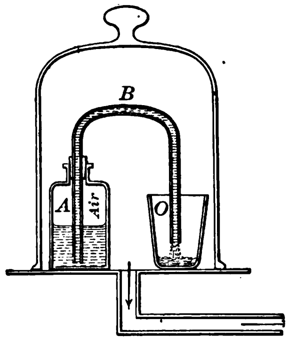

FIG. 72. — The bent tube is open at both ends.

The Buoyancy of Fluids

40. The Apparent Loss of Weight sustained by a Body immersed in a Fluid. — When a stone attached to a string is weighed first in air and again when suspended in a jar of water or any other liquid (Fig. 73), it is found that its weight in the liquid is apparently less than its weight in air.

FIG. 73. — The water supports a part of the weight of the stone.

Also if the jar of water is first carefully balanced, and the stone is then suspended in the liquid, it is found that the liquid seems to gain in weight as much as the stone seems to lose. This shows that there is no real loss of weight experienced by the stone, and that the apparent gain in weight of the liquid and loss in weight of the stone are due to the lifting action of the liquid upon the immersed stone. The liquid seems to gain weight in the same manner as a man would seem to gain in weight if, when standing on the scales, he should lift all or a part of the weight of some other body.

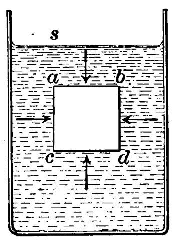

FIG. 74. — The upward pressure of the water on cd is greater than the downward pressure on ab.

The cause of the apparent loss of weight is the unequal weight pressure of the liquid upon the body immersed. Let $abcd$ (Fig. 74)

represent a body immersed in a vessel of water. Since for each point in the side *ac* there is a point on the side *bd* at the same depth where the pressure is equal and opposite, it follows that the total pressure against *ac* is balanced by the total pressure against *bd* without regard to the quantities of water on the two sides of the body. Upon every point of the upper surface *ab* the water exerts a downward pressure, the intensity of which depends on the vertical depth *sa*. Upon every point of the bottom *cd* the water exerts an upward pressure which depends upon the greater depth *sc*. Because the water is deeper at all points of *cd*, where it presses upward, than it is at the points of *ab*, where it presses downward, it follows that the water has a lifting action upon the body immersed, which is equal to the difference between these two pressures. By a similar line of reasoning we may show that whenever any body is immersed in any liquid or gas the total upward pressure of the fluid on the body immersed is always greater than the total downward pressure of that fluid on the body.

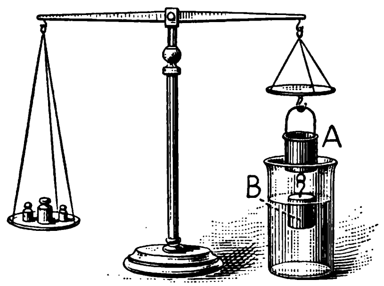

FIG. 75. — To prove Archimedes' principle.

The *excess of the upward over the downward pressure* of any fluid on any body immersed in it is called the ***buoyancy*** of the fluid. Buoyancy, then, should be thought of as an action of a fluid rather than a property of it, for there is no buoyancy when there is nothing either immersed or partly immersed.

Archimedes' Principle. The relation of Buoyancy to the Weight of the Fluid Displaced. — The relation of buoyancy to apparent loss of weight can be found by using a hollow brass cylinder and solid brass plug which has the same volume as the cavity. The cylinder and plug are first balanced as shown in Figure 75,

and then a vessel of any liquid is placed under the plug and raised until the plug is immersed. The lifting action of the liquid, or the buoyancy on the plug B destroys the balance. If the cavity A is now filled with the same liquid, the equilibrium is restored. In case the plug is only partly immersed in the liquid, then filling the cavity to the same depth as that to which the plug is immersed restores the balance. The experiment demonstrates that *a body when immersed or partly immersed in a fluid sustains an apparent loss in weight or a buoyancy equal to the weight of the fluid displaced.* This general truth is known as *Archimedes' Principle.*

In case the body is entirely immersed the *volume* of the body and the *volume* of the fluid displaced are equal; hence the apparent loss of weight is then the same as the weight of an equal volume of the fluid. Archimedes' principle can also be proved from a study of the pressure upon an immersed body. It has been shown (Fig. 74) that the buoyancy is the difference between the pressure on *cd* and that on *ab*. But the pressure on *cd* is as much greater than that on *ab* as the weight of the fluid which would fill the space occupied by the body, hence the buoyancy or excess of the upward pressure on *cd* over the downward pressure on *ab* is equal to the weight of the fluid displaced.

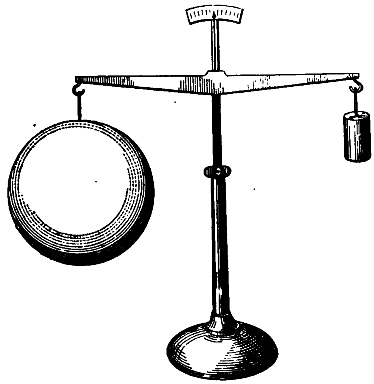

FIG. 76. — The closed sphere and contents balance the cylinder when they are in the air. In a vacuum the sphere over-balances the cylinder.

All fluids have weight, and because buoyancy is produced by weight pressure, Archimedes' principle is true for both liquids and gases. The closed sphere and cylinder (Fig. 76) balance each other when both are in the air, but the sphere over-

balances the cylinder when both are in a vacuum. For this reason the weight of a body in air is not its true weight, though most solids and liquids are so much denser than air that the difference between their weight in air and in empty space is such a very small part of their entire weight, that it is commonly neglected. Bodies which are very large in comparison to their weight — for example, balloons — frequently experience in the atmosphere a buoyancy equal to or even greater than their own weight.

4. **Conditions that determine Floating and Sinking.** — Let us suppose that a cubic centimeter of wood and a cubic centimeter of lead are both put into water and released in the positions shown in Figure 77. Reasoning from Archimedes' principle, we conclude that the buoyancy on each block is 1 gm., that is, the weight of 1 c.c. of water, for they each displace their own volume of water. Since the weight of 1 c.c. of soft wood is about .5 gm., the buoyancy upon the wood will exceed its weight, and the block of wood, when released, will rise until about one half of it is above the level of the water, in which position the weight of the water displaced will equal the weight of the block and the block floats. That is, a *floating body displaces its own weight* of the liquid in which it is floating. The cubic centimeter of lead weighs 11.3 gm., but the buoyancy or weight of water displaced is only 1 gm.; hence the water cannot support its entire weight, and the lead sinks when released.

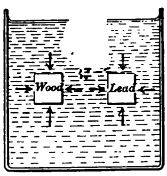

FIG. 77. — Bodies of equal volume experience equal buoyancy when in the same liquid.

A body sinks when it is not capable of displacing its own or more than its own weight of the fluid in which it is placed. By changing the shape of the given piece of lead — for example, making it into a thin hollow sphere or shell — it may then be capable of displacing more than 11.3 gm., its own weight of water. If so, it will then float when placed in water.

When put into mercury, the 1 c.c. of lead will always float, because the density of mercury, being greater than that of any piece of lead, lead is always capable of displacing more than its own weight of mercury.

Questions and Problems

1. When a body is immersed in any fluid, in how many directions is it pressed upon by that fluid? Are these pressures of the same intensity at all points? If not, where are they greatest?

2. Having found the direction of the greatest pressure of the fluid on an immersed body, tell what effect the excess of pressure in that direction must have upon the apparent weight of the body. What name is given to this action of a fluid?

3. Fix the attention upon a particular cubic foot of water at rest in a tank or reservoir. What is the actual weight of the cubic foot of [illegible]? Since it remains at rest, what must support its weight? [illegible]e the difference between the total upward and total downward p[illegible]sure of the other water on this cubic foot of water.

4. Imagine the cubic foot of water removed and its place taken by a cubic foot of marble, of iron, a cubic foot of wood, or a cubic foot of oil. Would the surrounding water exert the same pressure upon each of these as upon the cubic foot of water? How much would the upward and downward pressures differ? Compare this difference with the weight of each cubic foot, and explain why some sink and others float.

5. A certain block is 3 cm. thick, 4 cm. wide, and 5 cm. long; find (*a*) the volume of the block, (*b*) the weight of water it displaces when wholly immersed, (*c*) the lifting effect or buoyancy of the water upon the block.

6. If the block of the last problem weighs 450 gm. in air, state whether the block will rise or sink when released beneath the surface (*a*) of water, (*b*) of mercury. Explain.

7. Under what conditions does a completely immersed body displace its own weight of a fluid? less than its own weight? more than its own weight?

8. A block of wood when floating in a vessel of water displaces 320 c.c.; what is the weight of the wood?

9. Would a lifeboat having water-tight compartments carry a heavier load with these compartments empty or if they were filled with air? How much?

10. State the conditions under which a balloon will (*a*) rise, (*b*) fall, (*c*) remain at a given elevation. (Consider the term *balloon* as including the gas, the receptacle, the ropes, car, and occupant.)

11. What is the purpose in throwing out sand from a balloon? in letting out some of the gas? Explain how each produces the desired effect, and make plain the reason why the removal of 1 lb. of gas does not have the same effect as the removal of 1 lb. of sand.

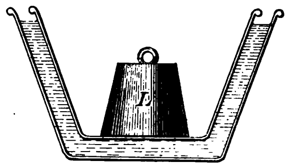

FIG. 78. — The principle used in the floating dock. A small quantity of water floats the inner dish with its heavy load L.

12. In reading a description of a new vessel we notice that its "displacement" is 20,000 tons net; what does this mean? A cargo is placed on the vessel; how does this affect the displacement?

13. State the conditions under which a body will rise in motionless air. Do these conditions explain the rising of smoke and dust?

14. Is a body attracted as much by the earth when it is in air as when in an empty space? Does it have the same apparent weight? Explain.

15. A piece of cork placed on one scale pan balances a certain piece of iron on the other when both are in the air; will they balance if both are in a vacuum? Explain.

16. In the air a pound of lead balances a certain roll of cotton; which is attracted more by the earth, that is, weighs more? Have they exactly equal masses?

17. Explain by reference to Figure 78 how a given quantity of water in a dry dock or canal lock may float a vessel many times its own weight.

18. Will a pressure of the finger on the sheet rubber top of a bottle (Fig. 79) compress the air at a', a, or both? Explain why the tube a falls and rises with a change of the pressure of the finger.

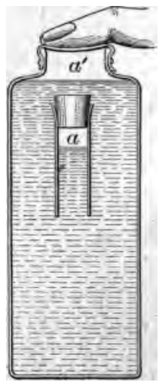

FIG. 79. — The cartesian diver. When the pressure of the finger increases, the diver falls.

42. Relative Density; Specific Gravity. — It has already been shown that the density of a body depends both upon its mass and its volume. If we were to select some one substance as a standard and compare the density of every other substance to that of the standard, we should obtain a set of results called the *relative* or *specific densities of substances.* The most suitable standard is water, the substance that is used most extensively for experimental and manufacturing purposes. Since the density of water is 1 gm. per cubic centimeter, the same number

which expresses the density of any substance in grams per cubic centimeter will also express its relative density when water is the standard. For example, since the density of mercury is 13.6 gm. per cubic centimeter, its relative density is 13.6. Though the mass of a body and its weight are not the same (see Sec. 9), it has been shown that at a given place the same relation exists between the weights of any two bodies as exists between their masses, or the weights of any two bodies are proportional to their masses. The *ratio of the weight of any body to the weight of an equal volume of a standard is called the specific gravity* (specific weight) *of that body.* Water has been selected as the standard for solids and liquids, and air or hydrogen for gases.

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{weight of equal volume of standard}}.$$

It follows, then, that the terms *relative density* and *specific gravity* have practically the same meaning, though derived by a somewhat different line of reasoning.

43. **Methods of finding Specific Gravity.** — Having determined what the term *specific gravity* means, it becomes plain that certain quantities must be known before we can compute the specific gravity of any substance. These quantities are (1) the weight of a given body of that substance and (2) the weight of an equal volume of the standard. Any method by which we can easily and accurately get these two quantities will then be a suitable method of finding specific gravity.

44. **Methods for Solids not Soluble in Water.** *Solids Denser than Water.* — The weight of the body in air is taken as its true weight.

The body is then attached to a cord suspended in water and its *apparent loss in weight* is found by subtracting its weight in water from its weight in air. According to Archimedes' principle, this loss of weight is the *weight of an equal volume of water.* By dividing the weight in air by the apparent loss in weight, thus found, we get the specific gravity.

Solids less Dense than Water. — If the object is less dense than water, it floats, but the apparent loss of weight can be found by attaching to it another body which will make it sink, called a sinker. The weight

(a) of the given body is found in air. We then find the weight (b) of the sinker alone in water, and then, the sinker and body having been fastened together, their combined weight (c) in water is found. Because the sinker alone weighs more in water than object and sinker together, the buoyancy of the water must support the entire weight of the body (a) and as much more as the body pulls upward on the sinker ($b - c$); that is, the entire buoyancy on the block is $a + (b - c)$. But the buoyancy is the weight of a volume of water equal to the volume of the body. Hence, the specific gravity of the body $= \frac{a}{a + b - c}$.

45. A Method for Solids Soluble in Water. — When a substance is soluble in water, the previous methods are not directly applicable. In this case we may find the specific gravity of the solid by first using as a standard another liquid in which it will not dissolve and then comparing the specific gravity of this liquid with water, the true standard.

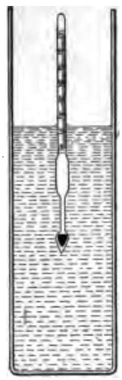

Fig. 80. — The hydrometer sinks until it displaces its own weight of the liquid in which it is floating.

46. Methods for Liquids. — The specific gravity of liquids may be readily found by weighing an empty bottle, then the same bottle full of water, and again when full of the given liquid. In this way we can get the weight of equal volumes of the given liquid and the standard. For this purpose bottles, called specific gravity bottles, are specially prepared by the apparatus makers, with the capacity of the bottle etched on the glass, thus avoiding the necessity of filling the bottle with water.

A much more rapid and fairly accurate method for finding the specific gravity of liquids is based upon the principle that a floating body always displaces its own weight of the fluid. Graduated glass tubes weighted below, so that they will stand upright, as shown in Figure 80, are frequently used for this purpose. They are called hydrometers, lactometers, etc., according to the kind of liquid for which they are intended. If this instrument sinks to a given depth in water, it is evident that it would sink to a greater depth in a less dense liquid (say kerosene) before it would displace its own weight. The instrument is graduated either to show the specific gravity directly or by reference to an accompanying table.

Since the weight pressure of a liquid depends upon its depth and its density, the relative density or the specific gravity of liquids may also be found by the principle shown in section 30. If two liquid columns balance each other, the vertical depths of the two liquids are inversely proportional to their relative densities or specific gravities.

For liquids that do not mix with water the U-tube is the most

convenient apparatus to use for the purpose (Fig. 81). In other cases an arrangement like that shown in Figure 82 is used. Here the atmospheric pressure is responsible for the rise of the liquids in the tubes, and the two columns, though they do not balance each other directly, balance the same part of the atmospheric pressure; hence their relative densities are to each other inversely as the vertical depths of the liquid columns, measured from the free surfaces in the dishes.

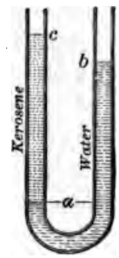

FIG. 81. — The specific gravity of the kerosene is to that of the water as depth *ab* is to depth *ac*.

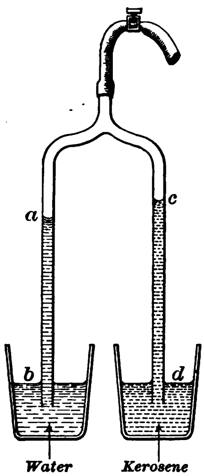

FIG. 82. — Since the air pressure at *a* is the same as that at *c*, the water column *ab* exerts the same pressure as the kerosene column *cd*.

47. The Value of Specific Gravity. — Since nearly every substance in its pure condition has a specific gravity different from other similar substances, it is evident that the specific gravity of a body is an indication both of the kind of substance and of its purity. Chemists, druggists, and manufacturers use the specific gravity of a substance as one of its valuable tests.

TABLE

SHOWING THE AVERAGE SPECIFIC GRAVITY OF A NUMBER OF COMMON SUBSTANCES

SUBSTANCE	SP.GR.	SUBSTANCE	SP.GR.	SUBSTANCE	SP.GR.	SUBSTANCE	SP.GR.
Aluminum	2.6*	Iron		Alcohol		Air (stand-	
Anthracite		(wrought)	7.8	(ethyl)	0.79	ard)	1.00
coal	1.5	Lead	11.3	Benzene	0.90	Ammonia	0.59
Brass	8.5	Marble	2.6	Ether	0.74	Carbon	
Copper	8.8	Oak	0.75	Mercury	13.59+	dioxide	1.53
Cork	0.24	Paraffin	0.89	Oil (linseed)	0.94	Coal gas	0.34
Ebony	1.2	Platinum	21.4	Oil			0.45
Glass		Porcelain	2.4	(turpentine)	0.96	Hydrogen	0.07
(common)	2.6	Poplar	0.45	Petroleum	0.80	Nitrogen	0.97
Gold	19.3	Silver	10.5	Water (pure		Oxygen	1.10
Ice	0.9	Tin	7.3	at 4° C.)	1.00	Steam (at	
Iron (cast)	7.4	Zinc	7.1	Sea water	1.025	100° C.)	0.47

Questions and Problems

1. What is the meaning of the expression "the specific gravity of copper is 8.8"? What will 1 c.c. of copper weigh in air? in water?

2. If 10 c.c. of chloroform weigh 14.8 gm., what is the specific gravity of chloroform?

3. A cubic foot of linseed oil weighs 58.8 lb.; find the specific gravity of linseed oil. What will be the weight of 1 c.c. of it?

4. A piece of brass weighs 904 gm. in air and 791 gm. in water; find the weight of an equal volume of water; find the specific gravity of brass. State the principle involved in this problem.

5. If the specific gravity of anthracite coal is 1.5, what will 1 cu. ft. of coal weigh (*a*) in air? (*b*) in water?

6. A certain piece of anthracite coal weighs 100 lb. in air; how much will it weigh in water?

7. A piece of ice will float with what portion of its volume above the surface (*a*) of fresh water? (*b*) of sea water?

8. How much will 10 c.c. of cast iron weigh in air? How much in gasoline, of a specific gravity of .66?

9. Compute the volume of 300 gm. of mercury.

10. A body having a volume of 8 c.c. weighs 54.4 gm. in water; what is its specific gravity?

11. A cork having a specific gravity of .24 and a volume of 1 l. will weigh how much in air? What weight of water will it displace when floating? What per cent of the cork will be below the surface of the water?

12. A piece of nickel weighs 170 gm. in air, 150 gm. in water, and 158.6 gm. in turpentine; find (*a*) the specific gravity of the nickel, (*b*) the specific gravity of the turpentine.

13. What weight of mercury is displaced when a block of iron having a volume of 100 c.c. is placed in it?

14. If when the block of iron, Problem 13, is floating, water is poured into the vessel until the block is completely covered, what will be the weight of the mercury and water which it now displaces? Will the block of iron be more or less deeply immersed in the mercury than before the water was put in? Calculate how much it will change. Make a drawing and explain.

15. A lump of sugar weighs 40 gm. in air and 20 gm. in alcohol; find the specific gravity of the sugar.

16. A piece of wood weighs 64 gm. in air, and a block of iron weighs 85 gm. in water. When the iron and wood are fastened together their joint weight in water is 33 gm.; find the specific gravity of the wood.

17. A certain bottle when filled with water weighs 156 gm., when filled with an oil it weighs 148 gm. If the empty bottle weighs 73 gm., find the specific gravity of the oil.

18. A boat displaces 580 cu. ft. of fresh water; find (*a*) the weight of the boat, (*b*) the weight of sea water (specific gravity, 1.025), and (*c*) the volume of sea water it displaces. Will the water line of a boat be nearer the deck when the boat is in sea water or fresh water? Why?

19. If a vessel holds 68 gm. of water, what weight of mercury will it hold? what volume of mercury?

20. If a certain bottle holds 408 gm. of mercury, what weight of alcohol will it hold?

21. What is the vertical depth of a column of water which counterbalances a column of benzine 27 cm. deep when the liquids are placed in the U-tube (Fig. 81)?

22. A druggist finds that a certain sample of alcohol contains 20 per cent water; what is its specific gravity? Another sample is found to have a specific gravity of .88; what per cent is water?

Apparatus for moving Fluids; Pumps

48. General Principles. — Quite a variety of machines, called pumps, have been designed for moving fluids. Their manner of working depends upon the characteristics of liquids and gases that have already been studied.

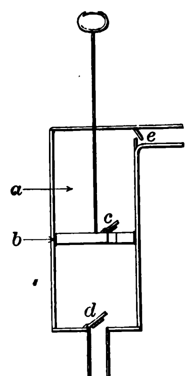

Fig. 83.

The simplest type of pump is that shown in Figure 83, where *a* is the cylinder or barrel, *b* the piston, *c* the piston valve, *d* the valve at the inlet, and *e* the valve at the outlet of the cylinder. The *piston* is a movable partition in the cylinder, designed to move the fluid. A *valve* is any contrivance, generally operated by the fluid itself, that will *permit* the fluid to go through an opening in the desired direction and *prevent* it from going through in the opposite or wrong direction. The simplest form of valve is similar to a door without a lock or fastening.

In constructing any kind of a pump, or in making a drawing of a pump, it is necessary to note the direction in which the fluid is to move through the pump and then place the valves so that they will open and close accordingly. In Figure 83 the valves are so arranged that the fluid must move upward; but when a downward direction of flow is desired evidently all valves must be reversed in their direction of opening and closing.

49. **Air Pumps.** — A pump used to remove air or any other gas from a closed vessel is called an *exhausting pump.* If, on the other hand, a pump drives air into a closed vessel, it is called a *compressing* or *condensing pump.*

The general type of pump shown in Figure 83 would serve either or indeed both of these purposes. If the closed vessel were attached to the lower or inlet tube, the air contained in the vessel would be gradually removed in the following manner: Let us suppose that the piston starts at the bottom of the cylinder and is being gradually drawn upward (Fig. 84). The piston valve c will be closed, by the air trying to get through, and the piston will then drive the air in the cylinder ahead of itself against the outlet valve e, which is thereby opened, letting the air gradually pass out of the cylinder. Meantime, the pressure below the piston having been diminished, the air in the closed vessel x will begin to expand. The expanding air opens the valve d and flows into the cylinder until the pressure becomes the same in both a and x. The actual quantity of air which comes out of x, by this expansion, depends upon the relative size of a and x. When the piston is thrust quickly downward, the air, starting back into the vessel x, closes valve d, which thus prevents the flow, while the outer air in attempting

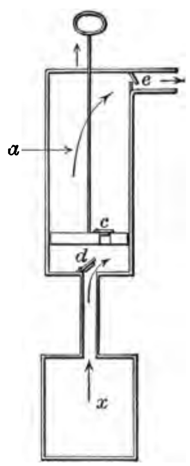

FIG. 84. — The rising piston drives the air out of a. The air in x expands.

to get back into the cylinder closes valve *e* and is stopped by it. The air in the cylinder, below the piston, is soon compressed enough to lift piston valve *c*, and then the piston moves on downward until it gets below the air in the cylinder. On the down stroke (Fig. 85) the air flows through the piston hole, but does not leave the pump. From this on the working is a repetition of that already described. Since each double stroke removes only a fraction of the air remaining in *x* after the previous stroke, it is plain that this pump cannot remove all the air from a given space. On account of leaks and other imperfections we soon reach the limit of exhaustion when pumping the air from a small vessel.

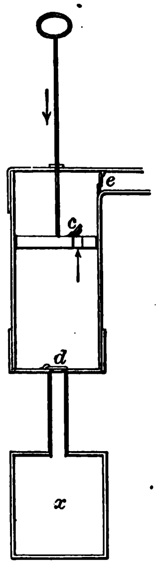

FIG. 85. — The descending piston moves through the air in the cylinder and thus gets ready to drive it out on the up stroke.

A common form of exhausting pump is shown in Figure 86, where the bell jar *D*, called the receiver, is the vessel from which the air is to

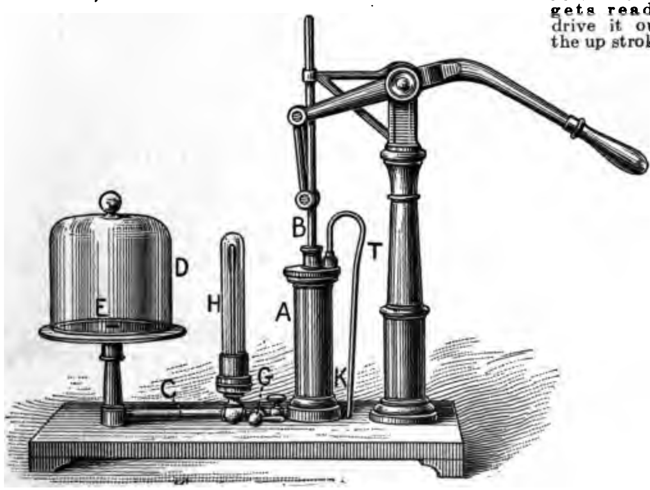

FIG. 86. — Air pump. *A*, the cylinder; *B*, the piston rod; *D*, the receiver; *E*, the outlet; *H*, a pressure gauge.

be exhausted. The working of this pump is identical in principle with that described, though the valves are generally of a more elaborate and satisfactory design.

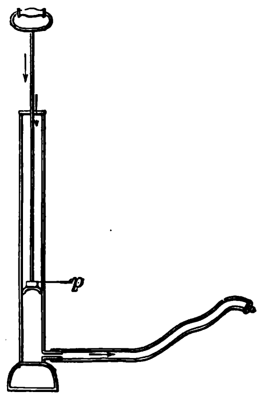

FIG. 87. — Foot pump.

By attaching vessel x to the outlet tube or by reversing all the valves in the pump shown in Figure 85, the air could then be compressed in x. The explanation of the working of a compression pump is practically identical with that already given for the exhausting pump. The common foot pump for the bicycle is a compression pump with the inlet valve omitted and the outlet valve placed in the tire.

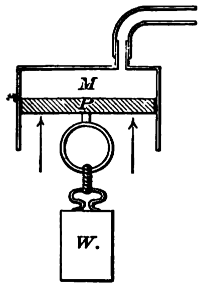

FIG. 88. — As the air is pumped out of M the piston, P, is pushed upward by the atmosphere.

The piston valve in such pumps is often formed by the leather of the piston itself, and the top or inlet valve is omitted (Fig. 87).

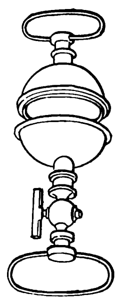

FIG. 89. — Magdeburg hemispheres. If the hemispheres fit tightly and the air within is pumped out, they are held together with a pressure which depends chiefly upon the area of their cross section.

Many interesting and instructive experiments can be shown with air pumps, particularly in connection with atmospheric pressure — lifting weights, Magdeburg hemispheres, fountain in vacuo, etc. (Figs. 88, 89, 90).

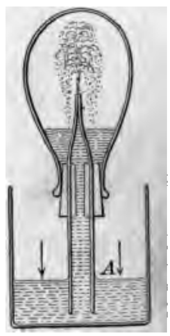

FIG. 90. — Most of the air is first pumped out of the vessel. It is opened when in the position shown.

The chief value of air or gas pumps is in connection with the operation of air brakes, compressed air engines, diving bells, and diving suits, the construction of electric light

bulbs, operation of ice-manufacturing machines, evaporation of sugar and other solutions, and in the construction of tunnels, piers, etc., where the air pressure is used to keep the water out of the space in which the men are working (Fig. 99).

The Air Brake. — The essential parts of the air brake equipment of a single car are shown in Figure 91. An air pump in the engine fills

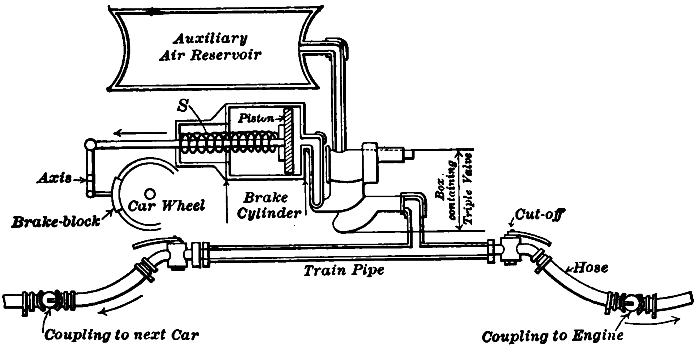

FIG. 91. — Diagram of the air brake.

the train pipe and auxiliary reservoir with compressed air at a pressure of about 70 lb. per square inch. Under these conditions a complicated valve, known as the triple valve, prevents the air from entering the brake cylinder, hence the brake is off. But when the pressure in the train pipe is reduced by the engineer, or by a breaking of the hose connection, the triple valve turns the air of the auxiliary reservoir into the brake cylinder, and the piston is pushed toward the left, thus drawing the brakes. Restoring the pressure in the train pipe throws the triple valve into such a position that the air in the brake cylinder escapes, and the pressure in the auxiliary reservoir is restored. The coiled spring *S* then pushes the piston back, and the brakes are off.

50. Pumps for moving Liquids. — Air pumps are used when surrounded by the atmosphere, which, on account of its great pressure, is ever ready to enter all joints or valves.

The cylinders of liquid pumps are commonly placed not in the liquid, but above it, and they are filled, with the aid of the

atmospheric pressure, through a pipe leading to the supply. On this account the atmospheric pressure is generally an important factor in the working of liquid pumps.

The relation of this pressure to the pumping can readily be appreciated by studying the following drawing representing a simple experiment. Let a piston be attached to a long rod, as shown in Figure 92, and pushed to one end of a long tube which it fits closely, and let this end be put into a jar of water. When the piston is raised, the water will follow it from *a* to the second position *b* as shown in the drawing. The rise of the water commonly attributed to "suction" is plainly due to the pressure of the atmosphere upon the water in the jar, and if the tube were indefinitely long, the water would follow the piston to a vertical height of about 34 ft. only, the exact height depending upon the barometric pressure. If mercury were used in this experiment, it would follow the piston about 30 in. only, or the height of the barometer at the given time, provided there is no leakage.

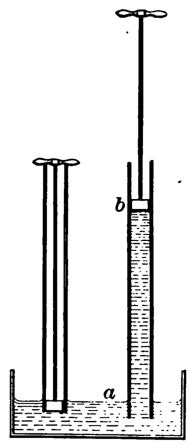

FIG. 92. — The atmosphere at *a* pushes the water after the rising piston *b*.

The Suction or Lifting Pump. — Returning to the general type of pump already shown (Fig. 85), we see that when used for liquids the outlet valve *e* may be omitted, and that the working of this pump at first, when filled with air, is like that already described as an exhausting pump, excepting that as the air is removed from the cylinder the liquid in the tank begins to come into the cylinder on account of the atmospheric pressure on the surface below.

Let us assume that the pump is full of water to the level of the outlet and the piston is at the top of the cylinder (Fig. 93). As the piston is pushed downward the water starts

back toward the tank, thus closing valve *d*, which thereby prevents it from flowing. The piston valve is then opened, by the upward pressure of the water, permitting the piston to get below the water in the cylinder. Since no water leaves the pump, this motion of the piston may be called a *preparatory stroke.* When the piston starts upward the piston valve is quickly closed, by the water trying to get below the piston again, and the piston now drives the water ahead of it up to and out of the outlet. Meantime, the pressure beneath the rising piston being diminished, the atmosphere, acting on the water in the tank, drives it up, opening valve *d* into the cylinder. This upward motion of the piston may be called a *working stroke.* Since the atmospheric pressure at its best cannot lift the water more than about 34 ft., it is useless to have the piston go more than that distance, *xy* (Fig. 94), above the free surface of water. The distance from the top of the piston stroke *y* to the outlet *e* may be as great as desired, hence this kind of pump may be used in a well of any depth provided the piston is kept within the proper distance from the liquid. On account of the part taken by the atmospheric pressure this is commonly called the *suction pump.*

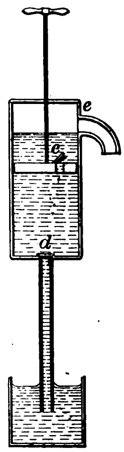

FIG. 93. — A lifting pump. The descending piston is getting beneath the water in the cylinder.

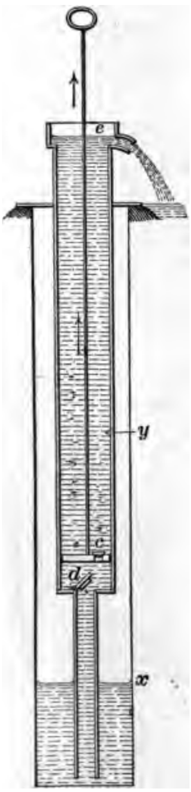

FIG. 94. — A pump for a deep well.

51. The Force Pump. — In many instances, particularly with large pumps, it is desirable to use a piston without a hole, thus dispens-

ing with the valve in the piston. In such cases the inlet and outlet are placed at the same end of the cylinder as shown in Figure 95. With this construction the cylinder is filled on the up stroke, just as in the suction pump, but emptied on the down stroke, thus dividing the work between the two strokes. There is no stroke that is simply preparatory. The same limitation exists as regards the distance from the free surface of the water in the well to the top of the piston stroke. But from the outlet valve to the place of final delivery there may be any desired distance or elevation, the limit depending upon the power used to work the pump and the strength of its construction.

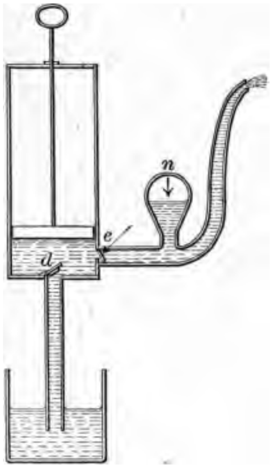

FIG. 95. — A force pump. Valve *d* is open on the up and *e* on the down stroke.

In fire engines and many other kinds of pumps it is desirable to attach an air chamber to the outlet pipe as shown at *n* (Fig. 95). The alternate compression and expansion of this air, at and between the times of the strokes, nearly equalize the pressure and produce an approximately steady flow in the pipe beyond the air chamber.

The heart of an animal acts in a manner similar to that of a force pump. The elastic walls of the blood vessels gradually diminish the thrust or pulse of each heart beat as the blood gets farther from the heart, until in the more distant and smaller blood vessels all sign of the beat or pulse has disappeared.

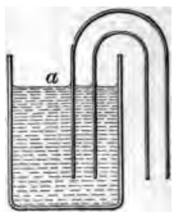

FIG. 96. — The tube below *a* is filled by the weight pressure of the water.

52. **The Siphon.** — When an open U-tube is placed in a vessel of water as shown in Figure 96, the water will rise, on account

of its weight pressure, to the same level *a* within the tube as in the vessel, neglecting any capillary action that may occur. If, however, the tube be first filled with water, closed at both ends, inverted, and placed in the jar of water as before, after both ends are opened, the water flows out of the tube and the jar (Figs. 97 and 98).

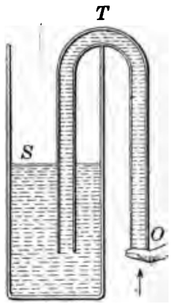

FIG. 97. — Starting a siphon.

Any tube used to transfer a liquid in the manner shown is called a siphon. By experimenting with such tubes we can readily establish the following facts:

(1) The level of the free surface of the liquid from which the flow occurs is always higher than that of the outlet or level of the liquid into which it flows; hence, measured vertically, the distance the liquid flows downward always exceeds the distance it flows upward.

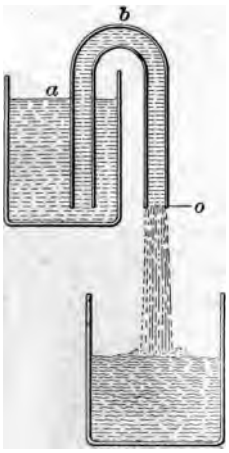

FIG. 98. — A siphon working.

(2) The speed of the flow for any tube is greatest when the difference of level is greatest.

(3) The siphon refuses to work when the distance of the upward flow exceeds a certain amount.

How the Siphon Works. — The flow of water in a siphon can be readily understood by giving attention to the atmospheric pressure and the weight pressure of the water. After a siphon has been adjusted let us first consider the atmospheric pressure. At *o* (Fig. 98) the atmospheric pressure is upward against the water in the tube. This *alone* would drive the water back towards the jar. At the same time the atmospheric pressure at *a* is transmitted by the water in the jar to the water in the tube, and this

alone would push the water outward through the tube. But the atmospheric pressure is practically the same at *o* and *a* though it is very slightly greater at *o*, hence the atmosphere alone is not responsible for the flow in a siphon.

The weight pressure in column *ab* is of less intensity than that of column *ob* as long as *o* is below the level of *a*, a necessary condition. Then the atmospheric pressure at *a* has opposing it the weight pressure of water having the depth *ab*, and the atmospheric pressure at *o* has opposing it the weight pressure of water having the depth *ob*. But since the pressure intensity of column *ab* is less than the pressure intensity of the longer column *ob*, there will be an unbalanced pressure in the direction of *abo*, and the water will run out at *o*. This reasoning holds true whether the two arms of the siphon have equal diameters or not. Briefly:

(At. press.) — (press. col. *ab*) $= x$, unbalanced press. outward.
(At. press.) — (press. col. *ob*) $= y$, unbalanced press. inward.
Since $ob > at$, then $x > y$.

This means that there is an unbalanced pressure from *a* toward *o*.

The top of the tube *b* may not exceed a certain distance above the free surface *a*; for when the height *ab* exceeds the height to which the atmospheric pressure can lift a column of the liquid used there will be a break of the liquid column at *b* and the siphon will not work. Plainly the *greatest vertical height* over which the liquid can be siphoned in any case *depends* upon both the *atmospheric pressure* at the time and place and also upon the *density of the liquid* which is being siphoned.

Questions and Problems

1. Let us suppose that the capacity of the cylinder of an air pump is 250 cu. in. and that of the receiver, including connecting tube, is 750 cu. in. After the piston has made one double stroke how will the pressure intensity in the cylinder compare with that in the receiver? What fractional part of the original mass of the air will leave the cylinder? Answer

the same questions for the second double stroke. (Assume that the piston begins its strokes at the top of the cylinder and that the weight of the valves is neglected.)

2. Illustrate, by means of a man and a wheelbarrow, the difference between the terms push and draw. Show that the common statement that air is "drawn" or "sucked" from a vessel by a pump is due to a misconception concerning the nature of gases.

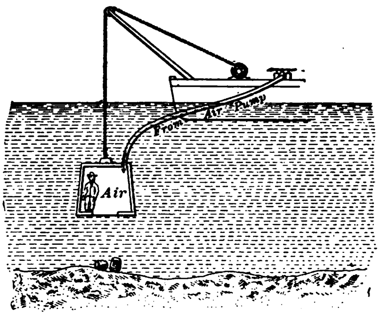

FIG. 99. — Showing the principle of the diving bell, the caisson, and the tunnel shield.

3. What must be the air pressure within a diving bell, a caisson, or a tunnel shield (Fig. 99.) to keep out the water where its greatest depth is 15 m. and the atmospheric pressure is 75 cm.? Solve when the depth is 50 ft. and the barometer 30 in.

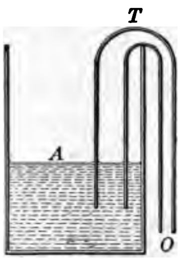

FIG. 100. — When filled, the weight of water in *AT* exceeds the weight in *TO*.

4. When the atmospheric pressure is 1000 gm. per sq. cm., what is the greatest height to which water will rise beneath the piston in a perfectly working pump?

5. How high would water rise beneath the piston when the barometer is at 80 cm.? How high would kerosene rise?

6. Find the greatest possible height above the original level over which a liquid will flow in a siphon when the specific gravity of the liquid is 1.5 and the atmospheric pressure 70 cm.

7. Suppose the diameter of the arm of the siphon in which the liquid rises is so large that the weight of water in that arm exceeds the weight in the other (Fig. 100). Will the siphon work as before? Explain.

8. Find the greatest height over which water may be siphoned in Denver, where the pressure is about 13 lb. per sq. in.

9. Explain the manner in which the "aspirating" siphon is started (Fig. 101).

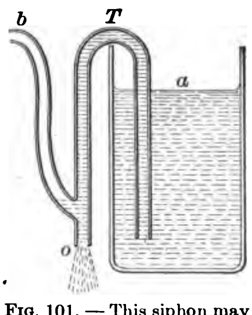

FIG. 101. — This siphon may be started by closing *o* with finger and sucking out air at *b*.

V. MOTION

HOW THE MOTION OF A BODY IS DETERMINED

53. **Position.** — The position of a body is said to be known when we have found its distance from another body and the direction of the straight line connecting the two bodies. Thus we roughly locate or determine the position of cities, mountains, and countries by stating their distance and direction from other cities, mountains, and countries or from reference lines and points like the equator or the poles. A more accurate method of determining position requires the selection of some representative point in each of the bodies concerned, as is the common practice with surveyors.

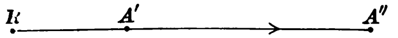

FIG. 102. — Linear motion or motion of translation.

A Change of Position. — The changing of position is called *motion.* But since position depends upon both distance and direction, either of which may be changed, *motion may consist in changing either distance or direction separately or both at once.*

Let A' (Fig. 102.), be the first position of a car with reference to a station R, and A'' the second position of the same car. In going from A' to A'' the motion of the car consisted *in a change of distance only.* The amount of this change in position can be expressed in centimeters, feet, or any other units of distance.

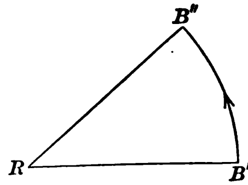

FIG. 103. — The motion consists in a change of direction only. Rotational motion.

Let us next assume that a body (say a nail in the tire of a wheel) moves from B' to B'' (Fig. 103.), along the arc of a circle, thus keeping at a constant distance from the center of the axle R. Now since all

the straight lines or radii connecting the body and the point of reference have the same length but different directions, *the motion in this case with reference to the axle* (*R*) *consists in a change of direction only.* The amount of change in direction in going from B' to B'' is measured by the angle between the lines $B'R$ and $B''R$. Figure 104 represents a motion involving *a change in both distance and direction* at the same time. Since we can easily imagine a body moving from C' to C'' in a countless number of paths, such as x, y, or z, this kind of motion may obviously be very complicated.

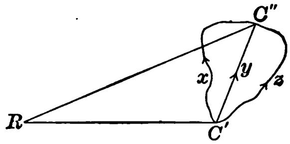

FIG. 104. — Motion from C' to C''.

A change in distance alone constitutes motion in a straight line, called motion of translation. A change in direction only gives motion in a circle, called rotary motion. Much confusion arises in discussing questions of motion through a failure either to select a standard of reference or to decide whether the motion is due to a change in direction, to a change in distance, or both. This confusion is added to by the fact that not infrequently a change in direction is completely ignored.

Motion and Rest are Relative. — When a body does not change its distance or direction from another body, each is said to be at rest with reference to the other. Plainly, then, both motion and rest as thus defined are relative, and a body may be said to be in motion with reference to one standard and at the same time at rest with reference to another. For example, a passenger may be said to be at rest relative to a car, but in motion relative to the earth.

The student should establish the habit of thinking and speaking of the *point of reference* as well as of the *body* moving in all discussions concerning motion. When not otherwise plainly indicated the earth is generally assumed as the standard of reference.

54. Rate of Motion; Speed; Velocity. — Time is always required for either of the changes in position called motion. If the number of units of distance passed over or the number of units of angle passed through is the same in each successive unit of time, the motion is said to be *uniform* (Figs. 105 and 106).

FIG. 105. — The body changes its distance from R equal amounts in each unit of time. A constant linear velocity.

When the motion is uniform we can find the distance passed over in a unit of time by dividing the whole number of units of distance over which the body moved by the whole number of units of time required to pass over it. The result thus obtained is known as the speed or linear velocity of the body. Briefly, the *rate of motion* is called *speed or velocity.*[1] For example, if a bicycle moves on a level road through a distance of 1000 ft. in 40 sec., the speed, if uniform, is 1000 ÷ 40, or 25 ft. per second. For uniform motion, the linear velocity is expressed thus:

$$\text{the speed} = \frac{\text{no. of units distance}}{\text{no. of units of time}}, \text{ or } v = \frac{d}{t}; \text{ hence, } d = vt.$$

In a similar way we find that the angular velocity when uniform is thus expressed:

$$\text{angular velocity } w = \frac{\text{no. of units of angle}}{\text{no. of units of time}}$$

The motion of the hands of a watch consists in a change of direction with reference to the axis around which they turn, and in a reliable timekeeper the rate of the change in direction is practically uniform. Since the minute hand goes through all possible changes of direction in 60 min., in 1 min. it will pass through an angle of

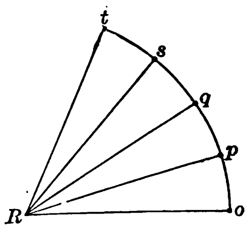

FIG. 106. — In moving along the path $opqst$ the body changes its direction from R the same number of degrees in each unit of time. A constant angular or rotational velocity.

[1] The scientific distinction between speed and velocity is not important for our purpose.

$360° \div 60 = 6°$. Then the angular velocity of any point on the minute hand is 6° per minute. Also, any point on the earth's surface describes a circle around the earth's axis in 1 day, or 24 hours; hence the angular velocity of any point with reference to the axis is $\frac{1}{24}$ of 360°, or 15°, per hour. Since it requires 1 hr. for the earth to rotate through 15°, the "time of day," or *sun* time, on any local clock will be 1 hr. behind or ahead of the local time of another clock which is 15° behind or ahead of the first place on the circle of rotation. Thus in Figure 107 if the arrow indicates the direction of the earth's rotation and A the place where the student is, then the local time at B is 1 hr. faster and that at C 1 hr. slower than at A, provided the arcs AB and AC are each 15°.

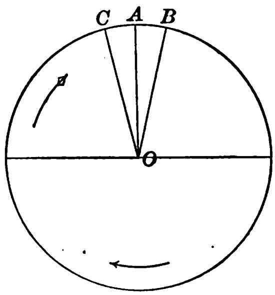

FIG. 107.

The idea of rotation is fundamental to the understanding of the relation of *longitude* to *local time*.

QUESTIONS AND PROBLEMS

1. The motion of a body may consist in what changes? Give examples of each.
2. When is a body said to be at rest? Give an example of a body in motion with reference to one standard and at rest with reference to another.
3. If two horses are pulling a carriage along a straight road, is there relative motion between them? When they turn from one street into another, is there relative motion? Give your reason in each case.

55. Variable Velocity. — If we give attention to the various bodies that are moving, we rarely find that their motion is uniform; that is, the velocity constant. Animals, rivers, winds, machines, move in complicated ways and with changing velocities. When the velocity of a body is changing, it is said to be *variable*. Observe the speed of a trolley car or of the wind

as shown by its effect on dust and other light objects. Each velocity is clearly variable, and moreover it does not vary in any regular way. Observe the motion of a pendulum as it swings to and fro. This velocity, too, is variable, but it varies in a regular way. There may be, then, a *uniformity in the change* of velocity.

This difference between an irregular rate of change and a uniform rate of change may be illustrated in the following way: \$1 per day is a uniform or constant income; \$1 for one day, \$2 for the next three days, then 50 c. for two days, etc., is not only a variable income, but one which varies in an irregular manner, but \$1 the first day, \$1.01 the second, \$1.02 the third, and so on, increasing 1 c. per day each day, is a uniformly changing income.

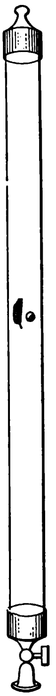

FIG. 108.— A feather and piece of lead have the same acceleration in a vacuum only.

56. The Rate of Change of Velocity; Acceleration. — If the velocity of a body undergoes an increase, it is said to be *positively accelerated.* When a decrease in the velocity is taking place, it is said to be *negatively accelerated*, or *retarded.* If the amount of *change* in the velocity is the same in each succeeding unit of time, the velocity is *uniformly accelerated.* A large lead bullet allowed to fall through the air from a high building gains in velocity until it reaches the ground. Since it gains practically as much velocity in the last second as it does in the first or any other second, it is said to be uniformly accelerated (Fig. 108). If we measure the *velocity gained* in the entire fall and divide this by the number of seconds during which the body is falling, we have found the velocity gained in the unit of time, or the *rate of gain in velocity.* This is called the *acceleration.* Careful experimenting has determined that at New York the acceleration of a freely falling body is about 980 cm. (32.16 ft.) per second for each second of fall. This means that during each second there is added to the previous velocity a velocity 980 cm. (32.16 ft.)

per second. Since the attraction of the earth for the body or its gravity is the cause of the body's fall, the rate at which a falling body gains velocity is called the *acceleration of gravity* and is usually represented by the letter g.

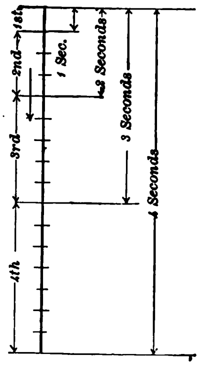

FIG. 109.—Graph of a freely falling body.

The value of g varies from 978.0 cm. per second (at the equator) to 983.2 cm. per second (at the poles). If we represent the number of seconds by the letter t and the velocity at the end of t seconds by V, then $V = gt$; that is, the total velocity gained is equal to the amount gained in 1 sec. multiplied by the number of seconds. This is true for a body falling freely with no initial velocity. But at the beginning of the fall $V = 0$, hence the average velocity for the time t will be one half of the sum of the two extreme velocities, or $\frac{1}{2}(0 + gt) = \frac{1}{2}gt$ = average velocity. The average velocity multiplied by the time will give the distance d.

Therefore $d = \frac{1}{2}gt \times t = \frac{1}{2}gt^2$.

(Compare the *amount of change in speed* and *rate of change in speed* respectively with the *amount of growth* and *rate of growth* of an oak, a cornstalk, and a toad stool.)

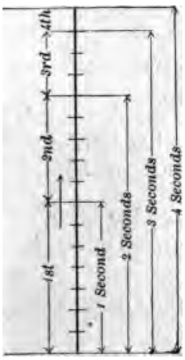

FIG. 110.—Graph of a rising body when not hindered by the air.

Laws of Falling Bodies.—The relations expressed by these formulas are usually known as the laws of falling bodies (Figs. 109 and 110). They apply strictly only to those bodies which fall without being hindered by the air or anything else (Fig. 108). Most falling bodies are so hindered by the air that their motion departs widely from these laws. Indeed, some of the best examples of a practically constant velocity are furnished by such objects as feathers and snowflakes

falling through still air. For this reason a study of the falling of bodies under common conditions is extremely difficult.

If the meaning of g is extended so as to include any uniform acceleration a, these formulas will apply to any uniformly accelerated motion, though such motions are rare. Any initial velocity i and the distance traveled on account of it must be added algebraically to the results obtained by using the formula as given above. Hence when there is initial velocity the formulas become $V = i \pm at$, $D = it \pm \frac{1}{2} at^2$.

Questions and Problems

1. Which can travel faster, a horse or an express train? Which can gain speed more rapidly? Which is capable of the greater speed? which of the greater acceleration?

2. One trolley car gains a velocity of 10 ft. per second in 1 sec. and another gains a velocity of 10 ft. per second in 1 min.; do they gain speed at the same rate? How do their accelerations compare?

3. If at the end of 120 seconds after starting, a railroad train has attained a speed of 1 mi. per minute, and 10 sec. after starting, a horse has the speed of 1 mi. in 3 min., which has the greater speed? Which has gained more speed? Which gains speed faster? Which has the greater acceleration?

4. A certain train starting at a station gains speed uniformly. If it acquires a speed of 2 ft. per second in each second, what will be its speed at the end of the first second? at the end of 10 sec.? at the end of the first minute?

5. If the train referred to in problem 4 continues to gain speed at the same rate, in what time will it acquire a speed of 30 ft. per second? In what time will it gain a speed of 1 mi. per minute?

6. What will be the average speed of the train for the first 10 sec.? How far will it travel in the first 10 sec.?

7. What is the meaning of the expression "the acceleration of a freely falling body is 980 cm. per second for each second"?

8. Express in both English and metric units the rate at which a body loses velocity when rising vertically, air resistance being neglected.

9. How much velocity will a freely falling body gain in 7 sec.? in the seventh second?

10. If a body falls from rest, how far does it fall in 5 sec.? How far in 6 sec.? How far in the sixth second?

11. How far does a freely falling body fall in the eighth second?

12. In how many seconds will a freely falling body acquire a velocity of 112 ft. per second? a velocity of 4410 cm. per second?

13. A body is shot vertically upward with a velocity of 320 ft. per second; neglecting the resistance of the air, find (*a*) how many seconds pass before it stops, (*b*) how high it rises, (*c*) with what velocity it is moving when it returns to the starting point, and (*d*) the time required to return.

14. A trolley car has a speed of 30 mi. per hour. At what rate must the velocity be decreased in order to stop the car in 10 sec.? to stop it in 4 sec.?

15. How far will the car of problem 14 move in the 10 sec. during which the brakes are stopping it? How far will it move after the brakes are applied if it stops in 4 sec.?

16. A body when thrown downward leaves the hand with a velocity of 10 ft. per second; what will be its velocity 1 sec. later? What at the end of 8 sec.? What will be its average velocity for the first 2 sec.? How far will it fall in 8 sec.?

17. Considering the mass as well as the weight or attraction of the earth, explain why a large body does not fall any faster in a vacuum than a small one does.

18. What is the velocity acquired in 1 sec. by a freely falling body in the latitude of New York? Name some cities where the rate of gain would be less. Some where it would be greater.

19. Explain why the weight of a body at any place depends upon both the mass and the acceleration produced by the earth's attraction, that is, why weight = mass × acc.; wt. = mg.

20. If the initial velocity of a body is 20 cm. per sec. and the positive acceleration is 12 cm. per sec. for each sec., find (*a*) the velocity at the end of 10 sec., (*b*) the distance passed over in 1 sec., (*c*) the distance passed over in 10 sec., and (*d*) the distance passed over in the tenth second.

57. Momentum. — For certain purposes it is desirable to consider the mass of the body moving as well as its velocity. The product obtained by *multiplying* the number of units of *mass* in a body by the number of units in its *velocity* is called the quantity of the motion, or the *momentum.*

$$\text{momentum} = \text{mass} \times \text{velocity}.$$

The chief value of this product, or momentum, is for purposes of comparison with other products similarly obtained in certain

discussions concerning the action between any two or more bodies. There is no definite *unit* of momentum, but for the purpose of comparison the momentum of any unit mass having any unit velocity (say 1 gm. moving with a velocity of 1 cm. per second) may be considered as a unit momentum.

The Relation of Momentum to Force.—Let us suppose that two balls having unequal masses (say 1 and 8 lb., respectively) are suspended from points in the ceiling about two feet apart, and a short piece of very elastic rubber is attached to the balls (Fig. 111). When the balls are held so that the cords are vertical, it is evident that the stretched rubber pulls on both balls with the same force but in opposite directions. If the balls are released at the same time, they begin to move toward each other and will meet at a point which depends upon their relative velocities. In the case assumed the distance passed over by the large ball is practically $\frac{1}{8}$ of the distance the smaller one has moved, consequently the velocity of the small one is 8 times the velocity of the large one, for each starts and stops at the same time the other does. Hence the momentum of the large body is equal to the momentum of the small one,

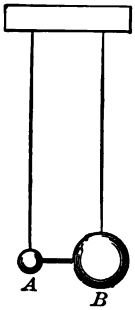

FIG. 111.

$$\text{mass} \times \text{velocity (of first)} = \text{mass} \times \text{velocity (of second)}$$

or

$$8 \times 2 = 16 \times 1.$$

The rubber acted for the same time and with the same force on both bodies, and we find that the same momentum was produced. In general, whenever any two free bodies, whether they have equal masses or not, are acted upon for the same time and with the same force there is the same momentum produced in each.

58. Concerning the Use of the Term "Force." — A body which

is giving motion to another body is said to be acting; and the body moved is said to be acted upon. Thus a hammer, when striking a nail, is said to *act upon* it.

But this action of the hammer may be of large or small magnitude; that is, there may be a heavy blow, 25 lb., or a light blow, 1 lb., upon the nail. The word *force* is here used to indicate *not the actor* but the *magnitude or intensity of the action* of one body upon another, whether they are in contact with each other or not. Thus we may say the *hammer acts* on the nail with a force of 25 lb., or 1 lb. It is common practice to say that *engines* move trains, *horses* pull wagons, *boys* throw balls. We propose to employ the same form of speech in the discussions of Physics. Strictly speaking, then, *bodies act, forces do not.*

A body may act but produce no motion. A book lying upon a table acts upon but does not move the table. Whenever it becomes desirable to distinguish between the body acting and the one acted upon, we will call the acting body *the agent* and the one acted upon *the load.*

Force is frequently defined as a *cause* of motion. This is very confusing to the beginner, particularly since the commonly given examples of so-called "forces acting" are really examples of one *body* acting upon another. The meaning of the term *force* which we have selected is in conformity with Newton's use of the word, and with this meaning the term can be used in connection with his laws of motion without confusion. In many discussions concerning motion we may for convenience speak of a force as "acting." It must be understood that this is a figure of speech which is justified only when, in general discussions, there is no need to direct the attention to the body acting. In a similar manner we speak of "the law" as convicting and punishing a prisoner when we do not care to name the particular judge, jury, or jailer.

59. How Forces are Measured; Units of Force. — A partic-

ular engine can get up speed most rapidly when the cars attached to it are few and empty. Pulling as much as he can, a horse gives velocity slowly to a loaded wagon, but rapidly to an empty one. Two horses doing their best would give velocity more quickly to either wagon than one horse can alone, but the loaded wagon will still gain velocity more slowly than the empty one.

This suggests that the force with which a body acts can be determined by the *mass* which it sets in motion and *the velocity given* to that mass *in a unit of time.* This can be shown experimentally, in a general way, by varying the masses of the balls and the pull of the rubber strip in the experiment suggested by Figure 111.

But the velocity given to a body in a unit of time is called the acceleration; hence, force=mass × acceleration, or $f=ma$. A body acts with *unit force,* when it *imparts a unit of velocity* to a *unit mass* in a *unit time. If in* 1 *sec., a body gives a velocity of* 1 *cm. per second to a mass of* 1 *gm. it is said to act with a force of* 1 *dyne.*

In this definition of the dyne it is assumed that only one body is acting on the gram mass.

In a similar way we may define the *poundal* as the force with which a body must act on a mass of 1 lb. to produce in 1 sec. a velocity of 1 ft. per second. Since their values are the same everywhere, the dyne and the poundal are called *absolute units of force.*

60. Gravitational Units of Force. — Since the earth at any place always attracts a given mass with the same intensity or force, we may use the *weight* of any *standard unit mass* as a *unit of force.* Such units of force are called *gravitational* or *weight units.* Forces, then, may be measured and expressed as a number of ounces, pounds, grams, or kilograms.

Thus when we say a body acts with a force of a pound we mean that it acts with the same force as the earth acts upon

or attracts a standard pound mass. These gravitational units of force are convenient, but because the weight of a given mass may change by changing its location, they do not have exactly the same value everywhere. At the latitude of New York 1 gm. weight = 980 dynes, and a five-cent piece or "nickel" weighs 5 gm., or about 4900 dynes. In the same latitude one pound weight is equal to 32.16 poundals.

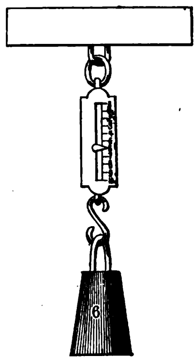

FIG. 112. — The weight of the iron is balanced by the pull of the spring.

Since force = ma and the weight of a body is the force called gravity, it follows that the entire weight of any body is equal to the number of units of mass multiplied by the acceleration of gravity, or weight = mg. When it is not convenient to compare forces directly with weights, we may measure them by means of other forces which have been compared to weights. The ordinary spring balance is thus used to measure forces in terms of the elasticity of a coiled spring (Figs. 112 and 113). In this instrument the force, expressed in grams or pounds required to pull the index to a given position, is determined by the maker and marked on the instrument. Any body when bringing the index of the spring balance to a given point on the scale must be acting with a force equal to that shown by the figures at that point.

61. Friction. — When we move or try to move a body by sliding or rolling it along the surface of another body there is always an action between them which hinders the motion. (Figs. 114 and 115.) The *resistance to motion* developed in this way is called *friction*. Friction, then, is not a thing that acts, but is a resisting force developed by the action between bodies. The amount of the friction in any case depends upon several things, the chief of which are

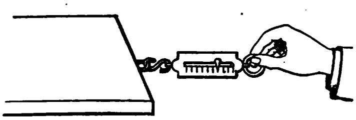

FIG. 113.

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the character of the surfaces in contact and the pressure between them. Friction is greater when the body is beginning to move than while it is moving. Since friction always is a hindrance to the relative motion of two bodies concerned, it is considered an advantage or a disadvantage, depending upon the object we are seeking to accomplish. We diminish friction by the use of oil on the axles and other bearings of a locomotive, but increase it by the use of sand on the track and the brakes.

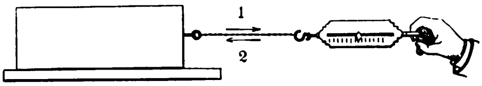


FIG. 114.

62. The Coefficient of Friction. — Let us suppose that a block of wood is pulled with uniform speed along a horizontal surface of any kind and that the force with which the agent pulls horizontally is measured by a spring balance (Fig. 114). If the force shown by the spring balance is divided by the weight of the block, that is, its pressure against the surface, we obtain a quantity known as the coefficient of friction. In general, the coefficient of friction is the ratio obtained by dividing the force required to counterbalance the friction by the force with which the bodies are held together.

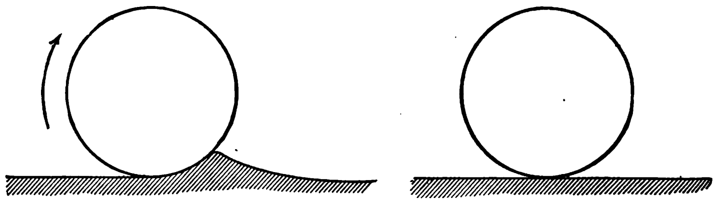


FIG. 115. — As a body ro'ls on a plane surface, both are deformed slightly.

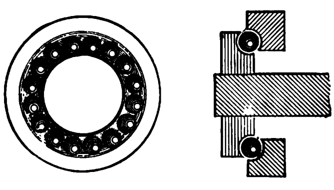


FIG. 116. — The rolling friction of the ball bearings is less than the sliding friction of the common hub and axle.

When a body is rolling in contact with a surface there would be no friction if there was no yielding of the surface with the consequent formation of a

hump in advance of the body (Fig. 115). This effect is very small with highly polished steel balls on a steel surface such as are used for ball bearings (Fig. 116).

Questions and Problems

1. When a gun weighing 10 lb. discharges a bullet weighing 1 oz. compare:
   (1) The force of the powder on the bullet with the force on the breech of the gun.
   (2) The length of time the powder acts on the bullet with the time it acts on the gun.
   (3) The direction of the motion of the bullet with the direction of motion of the gun.
   (4) The velocity of the bullet with the velocity of the gun.
   (5) The mass times the velocity of either with the mass times the velocity of the other.

2. Why does the pressure in the water pipes of a house become very great for an instant if the water which has been flowing rapidly is suddenly stopped?

3. State the distinction between a gram mass and a gram weight. Which changes with the latitude? Why?

4. If the pointer on a spring balance, graduated in grams, is pulled by a body hanging on the hook to the number 80, is the mass or the weight of the body 80 gm.? Would the same body pull the pointer to 80 at all places?

5. If the same body is put on one pan of an equal arm balance and counterbalanced by a piece of brass marked 80 gm., are the two weights or the two masses equal, or are both equal? Would they balance at all places?

6. If you observe that one body acts upon another and yet no motion results, what do you infer?

7. If an engine pulling with the same number of pounds gives twice the speed in 1 min. to one train that it can give in 1 min. under similar conditions to another train, what difference do you infer between the trains?

8. The earth pulls twice as much on a 2-lb. mass as on a 1-lb. mass. Prove that each should gain in speed as fast as the other.

9. Name a unit force based upon the weight of a definite unit of mass. Is it the same at all places? Give your reason. Name and define a unit of force which is based upon the acceleration produced in a definite unit of mass in a unit of time. Does it have the same value at all places? Why?

10. A force of 7 gm. is equivalent to how many dynes in New York? Will a force of 7 gm. in Panama be equivalent to a greater or less number of dynes? Why?

The Composition and Resolution of Velocities and Forces

63. Graphic Representation of a Velocity. — The velocity of a body is a measurable quantity, and any magnitude may be represented by a symbol or by another magnitude. The velocity of a body may therefore be represented by the length of a straight line and the direction of the motion by the direction of the line. Thus if the line AB (Fig. 117.) represents the motion of a car, then the length of AB represents its velocity, and the direction of the motion, if not marked, is either from A to B or from B to A.

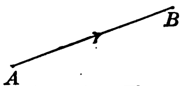


Fig. 117.—The graph of a velocity.

In case the line is read, the direction is indicated by the order in which the letters are named, but in other cases it is customary to use arrow heads to mark the direction.

The Composition of Velocities. — If a man is rowing across a river, his boat will acquire a velocity, relative to the earth, for two reasons—(1) the action of the current in the river, (2) the rowing of the man (Fig. 118). Let us assume that the speed of the river current is 4 mi. per hour relative to the earth and that the man can row the boat at a speed of 6 mi. per hour relative to the water.

If the man were to row directly up stream his velocity compared to the earth would be $6-4$, or 2 mi. per hour, relative to the earth. Here one of the velocities, being oppositely directed compared to the earth, subtracts from the other; or if we call the velocity in one direction positive and that in the opposite direction negative, then the velocity produced by a combination of the two, called the resultant velocity, would be their algebraic sum. If the man rows down stream, the velocities being similarly directed, the resultant would be their arithmetical sum.

If the river is 3 mi. wide, and he rows at right angles to the stream, he will land at the end of half an hour at a point 2 mi.

farther down stream than the point opposite the place where he started. On account of the rowing his boat will have moved across 3 mi. of water, for his velocity is 6 mi. per hour compared to the water, and in the same half hour the water has moved 2 mi. downward relative to the earth. The man's velocity compared to the earth, since he has moved both on account of the rowing and the current, is called a *resultant velocity.* Since the two velocities are neither opposite nor in the same direction, the resultant velocity is neither their difference nor their sum, but has a value greater than their difference and less than their sum. Let S (Fig. 118.) be the starting point, O the point opposite, and L the landing point. In relation to the water, the man's motion is represented by SO or $S'L$. In relation to the earth the motion of the water is represented by SS'. The resultant motion of the man in relation to the earth is represented by SL. Since we know SS' and $S'L$, we can find SL, thus:

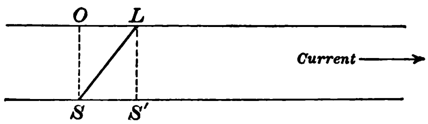


FIG. 118.—A composition of the velocity SO with the velocity SS' gives the velocity SL.

$$(SL)^2=(SS')^2+(S'L)^2, \text{ or } (SL)^2=4+9=13; \quad SL=\sqrt{13}, \text{ or } 3.6+.$$

In any case where a body is given *two* uniform velocities which are neither in the same nor in opposite directions the resultant velocity may be found by drawing, from a common point, two straight lines to represent the two given velocities and then constructing a parallelogram with these lines as two sides. The diagonal of the parallelogram represents *the resultant velocity. Any method of finding a resultant velocity either by the parallelogram of velocities or otherwise is known as the composition of velocities.*

When more than two uniform velocities are given at the same time, we find the final resultant by first finding a resultant of any two of the original velocities, then combining this

partial resultant with another original velocity, and so on until the final resultant is found. When the velocities are not uniform the composition is more difficult (Fig. 119).

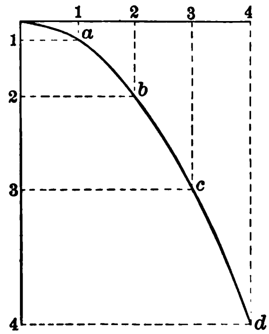


FIG. 119.—Graph showing the composition of a uniform horizontal with an accelerated downward motion. The numbers refer to the times; the letters show the positions at those times.

64. Composition of Forces. *How Forces are Represented.*—If we consider a force not as the cause of motion, but as a measurable action, a force as well as a velocity may be represented by a straight line. When a horse pulls, there are three things which completely describe the pull or force: (1) the magnitude of the pull or number of units of force, (2) the direction of the pull, and (3) the place where he pulls.

These are usually called the *magnitude, direction,* and *point* of *application* of the force. When we represent a force by a line, the *magnitude* of the force is represented *by the length* of the line, the *direction of the force* by one of the two *directions of the line,* and, usually, the point of action or application by one extremity of the line. Lines 1, 2, and 3 in Figure 120 represent three forces different in all respects, magnitude, direction, and point of application. Any convenient length may be selected to represent a unit force, but obviously in any problem the same length must be used throughout to represent the unit force, and the magnitudes of the forces are proportional to the lengths of the lines.

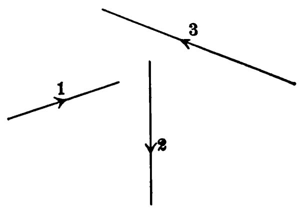


FIG. 120.

If two or more bodies act simultaneously upon a given body, it is often desirable to find the single force with which any one body would have to act to produce the same effect as all jointly produce. Thus we may find with what force one horse would

have to act to produce the same effect on a wagon as three men produce. The *process* of finding the *single force* which may be thus substituted for two or more forces is called the *composition of forces.* The single force when found is called the *resultant.* The equal and opposite force which would balance the given forces or balance the resultant is called the *equilibrant.*

Composition of Parallel Forces which have the Same Point of Application. — When three horses pull in the same direction upon a rope, as they do in towing a boat, the pull of each horse may be represented by a straight line, as shown in Figure 121. Since the three forces, *ab*, *bc*, and *cd*, are in the same direction, the resultant is their sum and is represented by a line (*mn*) which is the sum of the three lines. If one of the horses, instead of pulling in the proper direction, hangs back, or pushes as much as either of the others pulls, but in the opposite direction, it is obvious that his action subtracts from that of the other two horses, and the resultant will be the difference between the total force in one direction and that in the opposite. In this case the resultant will be equivalent to the pull of one horse. When two forces are parallel and in the same direction, the resultant is their sum; but when they are parallel and in opposite directions, the resultant is their difference. If we consider all forces in one direction positive and those in the opposite direction negative, the resultant of any number of parallel forces having the same point of application is always their algebraic sum.

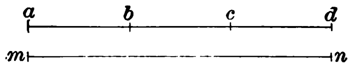


FIG. 121. — The resultant of parallel forces in the same direction is their sum.

Composition of Parallel Forces with Different Points of Application. — In the cases discussed the point of application of the resultant and equilibrant is obviously the same as the common point of application of all the original forces. But when the original forces have different points of application,

as when two horses, side by side, pull upon a bar, as shown in Figure 122, the resultant R is still their sum, but its *point of application* is located at neither A nor B, but somewhere between them. The exact location of this point (X) can be found experimentally, or it can be found by representing the forces, as shown in Figure 122 and Figure 123. In both cases X is so located that force $F' \times AX =$ force $F'' \times BX$. In Figure 122, F' and F'' are equal, hence X is equidistant from A and B. In Figure 123, F' being larger than F'', distance AX must be correspondingly smaller than distance BX.

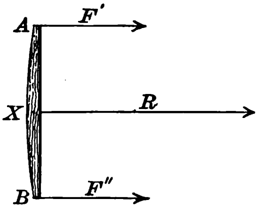


FIG. 122.—The resultant of F' and F'' is R with a po nt of application at X equidistant from A and B.

From this it appears that the distances of the point of application of the resultant from the points of application of the two original forces are inversely as the magnitude of these two forces. Hence:

$$F' : F'' : : BX : AX.$$

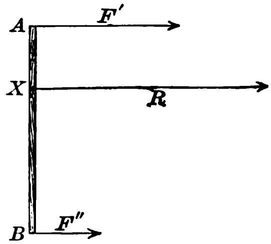


FIG. 123.—The point of application is nearer the larger force.

The best way to locate the resultant experimentally is to find the point of application of the equilibrant or counterbalancing force, as shown in Figure 124. The same point is the point of application of the resultant.

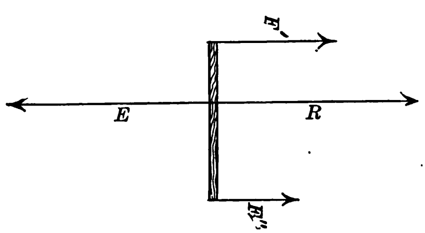


FIG. 124.—The equilibrant E is equal to and opposite to the resultant R.

65. Couple. — When a man pushes downward on one end C, of a thread cutter, as shown in Figure 125, and upward with an equal force on the other end A, the effect produced is rotational around B. The forces are opposite and equal, but they have

different points of application. Because no single force could produce the effect of these two forces, they have no resultant and no equilibrant. Any two forces which are opposite and equal with different points of application are called a *couple.* Though a couple has no resultant or equilibrant, the effect of one couple may be counterbalanced by another couple.

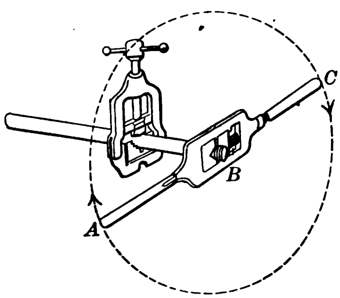


FIG. 125.—A plumber's thread cutter.

66. The Principle of Moment of Rotation.—Let CB (Fig. 126) represent a bar of wood supported at its center so that it may turn easily around this support. The line, A, around which all points in the rotating bar describe circles, or arcs of circles, is called the *axis of rotation.* If a single body, for example, a person's hand, acts upon this bar in any direction, except on a line passing through the axis, the bar will begin to rotate in consequence. The *rotational effect* produced by a body acting in this way is called the *rotational moment,* or simply the *moment of the force.* This rotational effect or moment has both a direction and a magnitude.

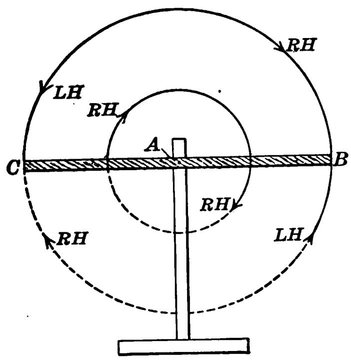


FIG. 126.—Showing right-hand (RH) and left-hand moments (LH) of rotation.

Direction of Moment.—When the rotation produced appears in the same direction as the hands of a clock or like the motion of an augur in boring a hole, the moment is said to be right-hand or + moment. When the rotation is in the opposite direction, it is said to be left-hand or − moment. Obviously these two directions of mo-

ment are purely relative and are useful only for comparison.

Two or more rotational moments in the same direction add to each other, but a + moment and a – moment oppose or one subtracts from the other. *When moments neutralize, they must be opposite in direction.* This is the *first condition of balancing or equilibrium of moments.*

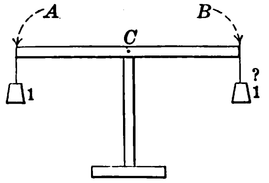


FIG. 127.—Equilibrium of moments. The force *A* is equal to the force *B* and the arm *AC* is equal to the arm *CB*.

The Magnitude of a Rotational Moment.— Let *AB* (Fig. 127) represent a bar 24 cm. long so mounted that it may turn freely at its center *C*. If equal weights (say 100 gm. each) be placed at *A* and *B*, they balance; hence their moments are equal and opposite. If we add to the weight or force at *B*, the bar begins to rotate in the positive direction, showing that the moment at *B* has been increased. The distances *AC* and *BC* being equal, the greater force produces the greater moment. If we return to 100 gm. as the two forces and move *B* toward *C*, the bar begins to rotate in the negative direction, showing that we have decreased the moment at *B* by decreasing the distance from the axis. Hence when the forces are equal, the one at the greater distance from the axis produces the greater moment (Fig. 128). By many trials we can prove that in all cases the magnitude of the moment *varies directly as the force and directly as the shortest distance from the axis to the line along which the force acts.* This distance is called the *arm* of the force. Hence the magnitude of the rotational moment of a force is equal to the force multiplied by the arm. *Moment = force × arm.* The *second condition of balancing or equilibrium of moments* is that their *magnitudes must be equal.*

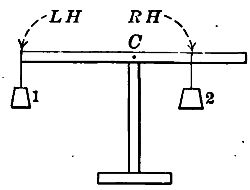


FIG. 128.—Equilibrium of moments. The product of each force by its arm is equal to the product of the other force by its arm.

Law of Moments. — When all the forces acting upon a bar, free to move around one axis only, balance each other, it follows that the sum of all the + moments must equal the sum of all the − moments, or their algebraic sum must be 0.

The use of an arm balance for weighing is based on the principle of moments. When the arms are equal, the weights or forces which balance are equal as in the simple scales, but by making one arm many times the length of the other a small weight can balance a large one, as in the steelyard (Fig. 129). In cases where the moments do not balance, we can easily find the unbalanced moment by finding first the sum of all the + moments, then finding the sum of all the − moments; the excess of either sum must represent the unbalanced moment. If the force required to produce equilibrium is known, we can then readily find the arm by dividing the force into the unbalanced moment, or, if the arm is given, we can similarly find the magnitude of the force required to neutralize this unbalanced moment.

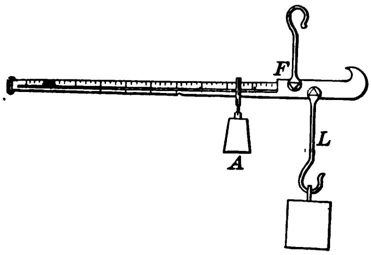


FIG. 129. — Steelyard. By making the arm of *A* very long a small weight at *A* may counterbalance a very large weight at *L*.

It should be noted that in this discussion the force at the axis is not considered, because there is no motion at that point. In case the forces are parallel and all act in the same direction, the magnitude of the force at the axis is the sum of all the others.

Questions and Problems

1. There are two parallel forces of 12 lb. each with points of application 8 ft. apart. Draw lines to represent the two forces and the equilibrant.

2. Find the point of application, direction, and magnitude of the equilibrant of two parallel forces the magnitudes of which are 6 and 16 dynes respectively and their points of application 44 cm. apart.

3. Two bodies A and B are placed in the opposite pans of a balance. When A is on pan x and B on pan y, they exactly balance, but when the bodies are reversed, A seems heavier than B. Are the bodies of equal weight? Are the arms of the balance of equal length? If not, which weight is greater and which arm is longer?

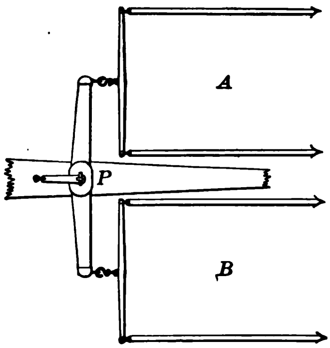


FIG. 130. — Horses A and B pull with equal forces.

4. Two horses are pulling on a wagon by means of a double tree (Fig. 130), at each end of which is a single tree. If the double tree is 4 ft. long, at what point on the double tree must it be attached to the wagon pole P that horse A may pull twice as much as B? at what point that A may pull $\frac{3}{4}$ as much as B?

5. In the steelyard (Fig. 129), the distance from the support to the place where the load hook is attached is $\frac{1}{2}$ in. Where must the sliding weight of 8 oz. be placed that it may balance a load of 10 lb.? of 15 lb.?

6. A man wishes to place a uniform bar of iron on end. It weighs 250 lb. and is 6 ft. long. With what force must he lift at the start if he takes hold at one end? if he takes hold 1 ft. from the end?

7. Find the direction, magnitude, and point of application of the resultant of two parallel forces of 18 and 24 gm. respectively, which are at two points 12 cm. apart. Make a drawing.

8. If the resultant of two parallel forces is 84 gm. and one of them is 36 gm., what is the other? If the distances from the point of application of the resultant to the point of application of the 36 gm. is 20 cm., what is the distance from point of application of resultant to that of the other force?

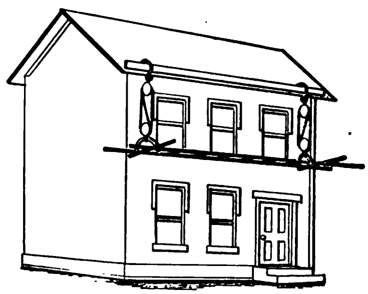


FIG. 131. — A painter's scaffold.

9. Two boys, x and y, carry a pail of water on a stick 6 ft. long, one boy having hold at each end. If the pail weighs 30 lb., where must it be placed so that each boy will have 15 lb.? where, so that x may have 20 lb.? where, so that he may have 24 lb., neglecting the weight of the stick?

10. A painter's ladder is suspended horizontally by means of two

ropes (Fig. 131). When the painter gets on the ladder, there is an increased tension or pull on one rope of 48 lb. Find how much the tension on the other rope is increased if the painter weighs 160 lb. Find the distances, from where the man is, to the two ends of the ladder if the distance between the two supports is 18 ft.

67. Composition of Forces not Parallel. — When two forces are neither parallel and opposite nor parallel and in the same direction, the resultant is neither their difference nor their sum, but must be greater than their difference and less than their sum. Let AB and AC represent the magnitude and direction of two forces at right angles to each other with a common point of application A (Fig. 132). The effect produced by each force will be the same whether acting alone or in conjunction with the other force; hence at the end of 1 sec. the body acted upon will be as far to the east of A as B is and as far to the north of A as C is, thinking of the page as a map.

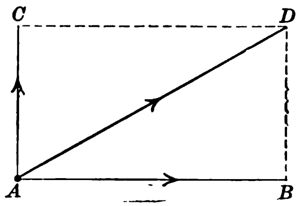


Fig. 132. — The composition of two forces at right angles to each other. The parallelogram of forces.

Since the point D fulfills these conditions, at the end of 1 sec. the body will be at D, having moved along the path AD. It follows that a force, represented in direction and magnitude by AD, if substituted for the two forces AC and AB, would produce the same effect as these two forces, hence AD is their resultant. Since the length of the line AD can be found by a familiar mathematical principle ($AB^2 + AC^2 = AD^2$), the magnitude of the resultant is easily found when the original forces are at right angles to each other.

When the directions of the forces do not form a right angle, the method of finding the resultant, by construction, is identical with that given above. For example, let OM and ON (Fig. 133) represent two forces at any angle; then the re-

sultant can be found by completing the parallelogram of which OM and ON are two sides. The line OP will represent the magnitude and direction of the resultant. The magnitude of OP can be found by direct measurement, but cannot be calculated from OM and ON and their included angle without the use of plane trigonometry. This geometrical method of finding the resultant of two forces is known as the *parallelogram of forces.*

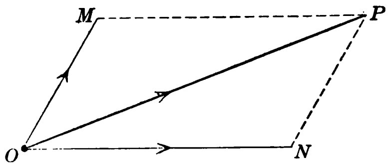


FIG. 133. — A parallelogram of forces when the original forces are not at right angles. The resultant is OP.

When the resultant of more than two forces not parallel is to be found, we may select any two of them and first find their resultant by the use of the parallelogram of forces, then use this partial resultant with another of the given forces to construct another parallelogram, and so on until the final resultant is obtained.

The Resolution of Forces. — By a reversal of the order of the reasoning involved in the method of composition of forces, or method of finding the resultant, we may find *two or more forces which might be substituted for an original force.* Thus we may let a line representing a given force be the diagonal of a parallelogram, and by completing the parallelogram find two forces which jointly would be equivalent to the given force alone.

This process is called the *resolution of forces.* Plainly, any number of parallelograms could be constructed with a given line as one of the diagonals; hence, in the process of resolution we must know, in addition to the original force, (1) the direction and magnitude of one of the components wanted or (2) the direction of both components.

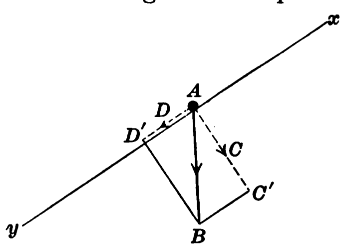


FIG. 134. — The resolution of forces. The force AB has been resolved into the forces AC' and AD'.

Thus in Figure 134 a given force AB is to be resolved into two components, one in the direction AC, perpendicular to a surface, XY, and the other in direction AD, parallel to the surface. Completing the parallelogram, we find the two components AC' and AD'.

The values of these forces may be easily found when the angle ABC' is 45°, 30°, or 60°. Other cases require a knowledge of trigonometry.

Questions and Problems

1. A motor boat can travel with a speed of 12 mi. per hour relative to the water. What will be its velocity relative to the earth when it is going up stream in a river which has a current of 5 mi. per hour? How long will it take the boat to cross to the opposite shore on a line at right angles to the bed of the stream if the river is 2 mi. wide?
2. Find the resultant of 30 lb. north and 40 lb. east. Use a drawing and represent both the resultant and equilibrant.
3. A ship is moving at the rate of 20 ft. per second through the water; a man walks across the deck at the rate of 4 ft. per second. Find the man's velocity relative to the water.
4. Two players strike a basket ball at the same instant, one with a force of 25 lb. toward the west and the other with a force of 35 lb. toward the south. Find the resultant force.
5. A ship is moving northwest with a speed of 16 mi. per hour. Find its equivalent westerly and northerly motions. Make a drawing.
6. A picture weighing 60 lb. is supported by a cord passing over a nail and attached to the sides of the picture in the usual way. If the two parts of the cord make an angle of 90° at the nail, find the pull or tension on the cord.
7. What effect would an increase or a decrease in the length of the cord in problem 6 have on the tension of the cord? Give your reason in each case.

68. The Attraction called Gravitation. — Any action between two bodies which results in their being drawn or urged toward each other is called attraction. It has been shown, chiefly by astronomical observations, that every particle of matter in the universe attracts every other particle. This attraction is called *gravitation*. The amount of the attraction in any case

depends upon two things, the masses of the bodies attracting each other, and the distance between them. The law according to which gravitation varies was discovered by Sir Isaac Newton and is known by his name.

It may be stated as follows:

The *gravitation between any two bodies varies directly as the product of their masses and inversely as the square of the distance between their centers of mass.*

Weight or Gravity. — The most familiar example of gravitation is the attraction between the earth and any body on or near the earth's surface.

In this case the attraction is called *gravity,* or more familiarly weight. Gravity should not be thought of as the *cause* of weight, but rather as a less familiar term to designate the same earth pull which is commonly called weight. Because the earth is not a perfect sphere a given mass may always be on the surface of the earth, yet undergo a change in weight on account of a change of location. The same object taken from a point at the sea level on or near the equator to another point at the sea level considerably nearer either pole will have its weight slightly *increased.* This is because the distance between the two centers of mass has been decreased. For a similar reason an object weighs a little more at the sea level than on the top of a high mountain. In both of these cases the mass of the given body does not change with a change of location, but its weight does.

As already stated, the weight of a body at any place is the attraction between it and the earth at that place. If two bodies have the same weight at a given place, they must also have the same mass. Hence we determine the mass of a body by the same method that we use to determine weights. The change in weight produced by a change of latitude or elevation is so small that it need not be taken into account unless the masses involved or the changes in location are very great.

The Direction of the Earth Pull or Weight. — When a heavy body is suspended by a cord from a single point, the direction of the cord after the body comes to rest is called a plumb line or vertical line (Fig. 135). Vertical lines, if continued, would all meet approximately at the earth's center; hence they are never strictly parallel, though practically so, provided they are near to each other. Any line at right angles to the vertical is called a horizontal line. Horizontal lines are really tangents to the earth and only when the points involved are near, may we consider the horizontal at one point as the continuation of the same straight line as the horizontal at another point.

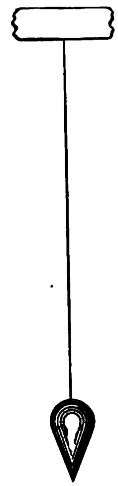


FIG. 135. — A plumb line or a vertical line.

69. Center of Gravity; Center of Mass. — If a piece of cardboard is supported by a pin run through it, at any one of the points, A, B, D, (Fig. 136), so that it may turn freely, it is found that the card in each case comes to rest with one particular point always in the vertical line passing through the pin or support. If the pin is then run through this point, the card will remain in any position in which it may be stopped. The point, C, thus roughly found is called the *center of gravity* or *center of mass* of the card.

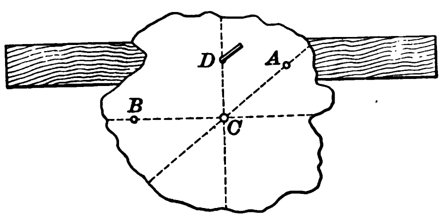


FIG. 136. — Center of gravity C, found by suspending body at different points, A, B, D.

Every other solid which can be similarly supported or be supported by a cord attached at different points will likewise come to rest with its center of gravity always in the vertical line passing through the supporting point. Though every molecule in a body has weight, the body as a whole acts as if its weight were all

located at its center of gravity. In all cases, then, where the *weight* of a body and *its distance from any point* are involved, we must measure the distance from the center of gravity of the body to the axis or other point concerned. Further, to determine whether a body is higher or lower after a given motion, we must observe the position of the center of gravity before and after the motion. The body as a whole moves in the same direction and as far as its center of gravity moves.

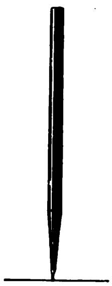


FIG. 137. — Shows unstable equilibrium.

When the entire weight of a body is balanced by a single force, this force or equilibrant must be equal to the sum of the weights of all the molecules, and its point of application must be either the same as that of their resultant or in a vertical line passing through it. It follows, then, that the center of gravity is the point of application of the resultant of the gravity or weight of all the molecules of a body.

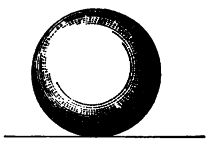


FIG. 138. — Neutral equilibrium.

When the weight of a body is supported or balanced so that the body does not move, it is said to be in equilibrium. If a body is so balanced that when slightly rotated about its support and released it will return to its former position, the body is said to be in *stable* equilibrium. Bodies with one or more plane surfaces are likely to have stable equilibrium in different positions; bricks, blocks of wood, beams, are familiar examples.

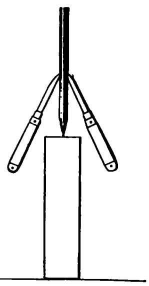


FIG. 139. — The combination of bodies is stable.

A body supported at a point or on a straight line below its center of gravity and then slightly rotated about the support will either fall or remain in its new position when released. If it falls as a pencil does (Fig. 137), it is said to be in *unstable* equilibrium, but when it remains in the new position as

a sphere does (Fig. 138), it is said to be in *neutral* equilibrium.

Objects firmly attached to the pencil as shown in Figure 139 may so lower the center of gravity, of the combination, that it falls below the point of support, thus producing stable equilibrium.

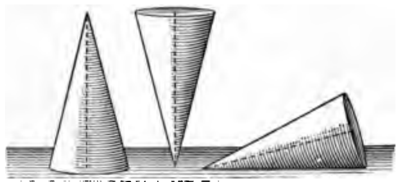


FIG. 140.— Illustration of three kinds of equilibrium.

The Center of Buoyancy. — When a body is floating partly immersed in a liquid, the center of gravity of the liquid displaced is called the *center of buoyancy.* A floating body when let alone assumes the position in which the center of gravity is as low and the center of buoyancy as high as possible. Thus a uniform rectangular block will float in position *a* rather than in position *b*, or *c* (Fig. 141), for the center of buoyancy is highest in position *a*, though the center of gravity is on the same level in all positions. On the other hand, the weighted hydrometer (Fig. 80, page 74) assumes the erect position because the center of gravity is then below the center of buoyancy. Boats are made more stable by making them wider at the top than at the keel, thus raising the center of buoyancy, and by placing the densest materials as low as possible, thus lowering the center of gravity of the boat.

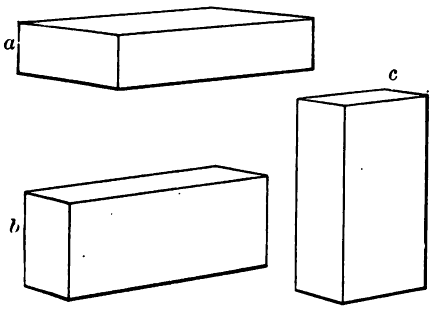


FIG. 141.— A rectangular block of wood.

70. Stability of Solids. — It is sometimes desirable to know how much horizontal pressure a solid will withstand before it

will begin to upset. This pressure serves to measure the stability of the body. Chimneys, monuments, bridges, boats, tables, chairs, are all examples of bodies which require considerable stability in their construction, exposed as they are to the action of the wind and other bodies.

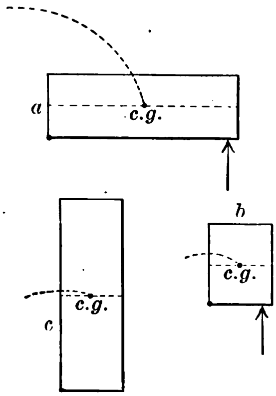


FIG. 142. — Showing the location of the center of gravity and the amount it is elevated as the block is upset.

The stability of a rigid body which is not fastened to another depends upon three things: (1) the weight of the body, (2) the location of the center of gravity, and (3) the base of support. To get a clear understanding of these points let us experiment with a brick and a wooden block of the same size and shape. On account of its greater weight the brick requires more pressure to upset it when placed in any given position than does the block when in a similar position. Since the two bodies are alike in other respects, the brick is more stable because it has the greater weight. The brick placed on end (Fig. 141) is in a less stable position than when lying on its edge, for in the first case, the center of gravity being higher, the weight of the body is lifted less when the body is being upset, as shown by the curved line in the figures (Fig. 142).

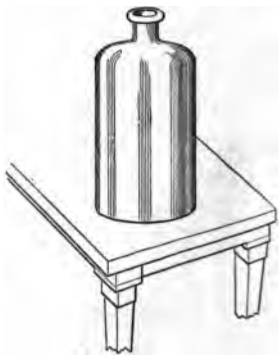


FIG. 143. — The same horizontal force is required to upset the bottle without regard to the direction of application of the force.

If the brick is placed in the position shown in Figure 142, *a*, it is in the most stable of all positions, because the center of gravity is the lowest possible. The larger the area of the base of support, the more stable is the body. If the base is a circle and the vertical line through the center of gravity passes through the center of the circular base, the body is equally stable when tested in all directions; for example, a cylinder or cylindrical bottle (Fig. 143), standing on end. If the base is not circular, or if the vertical line through the center of gravity falls nearer to the outside of the base at some points than it does at others, the body is not equally stable in all directions.

Questions and Problems

1. How could you find the center of gravity of a baseball bat or tennis racquet? Suggest some changes by which the center of gravity of a baseball bat may be changed without affecting the total weight.

2. How could a carpenter find the center of gravity of his hammer? If he knows the weight of the hammer, make a drawing and suggest how he could, by balancing a package of nails on his hammer handle, find their weight.

3. What is the object of the thick metal keel in a racing boat? Why place it so low?

4. Give a reason why sailors consider that a large load of lumber is a dangerous cargo, especially for a sailing vessel.

5. Examine a hydrometer and explain why lead or mercury is placed in one end of it.

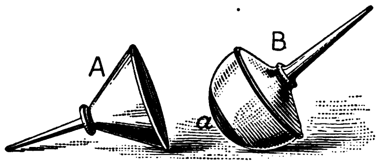


FIG. 144.

6. Explain why the oil can *B* in Figure 144 will assume the erect position and why *A* will not.

VI. ENERGY AND WORK

71. Moving Bodies can do Work. — A moving body can produce results which the same body at rest cannot. Thus a moving hammer can give motion to a nail. Whenever any body puts another into motion, the *body* producing the motion is said *to do work upon the other. The ability to do work is called energy.* The moving hammer may do work upon a nail, hence a hammer has energy when in motion. Similarly, engines, horses, bullets, and all other moving bodies have energy; that is, they have the ability to put other bodies in motion or to do work. But whether a body is moving or not, if we can show that it has the ability to do work, we conclude that it must have energy. All the changes which take place in the material universe are due to the energy of the bodies which produce them.

72. Types of Energy; Kinetic and Potential. — That energy of a body which is known to be due to its motion is called *kinetic energy.* A moving baseball, a flowing river, a falling raindrop, all have *kinetic energy.*

Whenever we can prove that a body is moving, whether its mass is large enough to be seen or as small as a molecule, we call its energy of motion kinetic energy.

There are many cases, however, when we have good reasons for believing that a body has energy yet we cannot show that this energy is due to any kind of motion (Figs. 145, 146). In all such cases the energy is called *potential energy.* For example, when the spring in a roller window shade is coiled by pulling down the shade and the catch prevents the shade from moving,

we cannot say that the spring has kinetic energy. But because it is able to lift the shade, that is, to do work, the spring, though not in motion, must have energy. We conclude that there is another kind of energy, which is not energy of motion; this form we call *potential energy.*

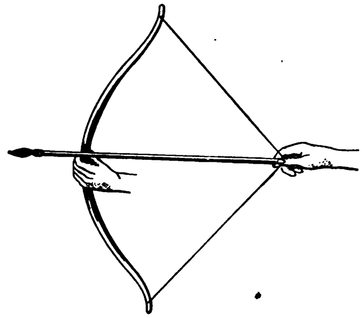


FIG. 145. — In bending the bow the hand does work. While bent, the bow is said to have potential energy.

There are two general *types* of energy. The one is the energy of motion, or kinetic energy. The other is the unexplained type, or potential energy. Potential energy is sometimes called "energy of position." When a stone is being lifted to its place in a wall, work must be done, or kinetic energy given to it on its way up. It may remain in the wall for an indefinite period, but if it be allowed to fall to the ground, a quantity of kinetic energy may be reproduced equal to that which disappeared in the lifting of it. When at rest upon the wall the energy given to the stone can no longer be called kinetic, hence it is frequently called the *energy of position,* an example of potential energy. It must be noted that this does not explain potential energy. Since position depends upon a distance and a direction, plainly the energy of a body could not depend upon position alone. In the case of the window shade spring, the energy depends upon the elasticity as well as the relative position of the parts of the spring, and in the case of the lifted

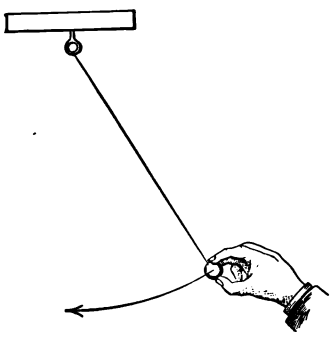


FIG. 146. — The displaced pendulum ball is said to have potential energy. When released, it moves without being pushed.

stone the energy depends upon the unexplained attraction of the earth as well as its position.[1]

73. Meaning of the Expression "Doing Work." — A man carrying bricks up a ladder is doing work. If he stops moving the bricks and merely holds them for a time, he is not doing work upon the bricks. A horse pulling upon a load which he cannot move may become tired and exhausted, but, in the sense in which the term *work* is used in physics, he is not doing work upon the load. *Engines, animals, levers, and other machines do work only when they move things.* A marble rolling along the table strikes another marble and sets it in motion. The first marble does work upon the second. But the first marble loses motion or energy at just the same rate that the second marble gains it (Fig. 147). Here the doing of work consists in the transferring of energy.

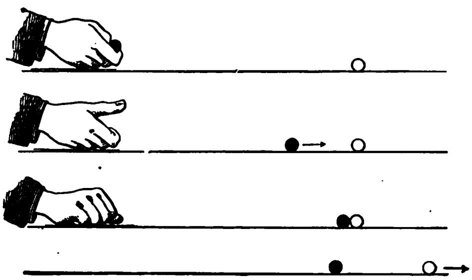


FIG. 147. — The thumb does work upon the black ball which in turn does work upon or gives kinetic energy to the white one.

Again, if two balls are suspended from a long horizontal cord xy, as shown in Figure 148, and one (a) is set swinging transversely to the cord xy, the other ball (b) will gradually receive motion or kinetic energy, until finally it will be swinging through about the same arc that a had in the

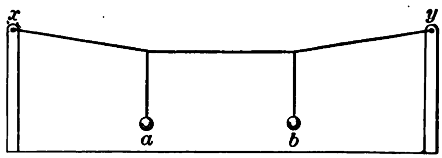


FIG. 148. — Energy may be transferred through the cord xy from a to b or in the reverse direction.

[1] *Kinetic* energy may be *compared* to *cash* in one's hand, but potential energy resembles credit at the bank obtained by depositing cash, which credit may again be converted into cash.

beginning. Meantime a loses its motion or kinetic energy as fast as b gains it, and finally, when b has the most energy, a has the least or even none. The process will now be reversed, b giving its energy to a. Here again we see that *doing work may consist in transferring energy. The body which gives up the energy, or produces the motion, is said to do work, and the one which receives the energy is said to have work done upon it.*

If we bend a piece of stout wire back and forth rapidly, we find that the wire has been heated (Fig. 149). We are conscious of doing work, but in this case the doing of the work results in the production of heat. The mechanical energy imparted to the wire assumed the form of heat. In other ways that can be better understood during the study of the various departments of physics, namely, heat, sound, electricity, light, etc., it can be shown that *doing work may consist in transforming any one kind of energy into energy of another kind. In brief, we conclude, then, that the doing of work consists in either the transferring or transforming of energy, and that the amount of work done is equal to the amount of energy transferred or transformed.* In some cases a part of the energy is transferred and another part is transformed. For example, the carbon filament of an electric lamp transmits one part of the energy of the current and transforms another part of it into heat and light. In other cases the same energy may be both transferred and transformed. For example, a locomotive transforms heat energy into mechanical motion and then transfers it to a train of cars. The motor in the trolley car transforms electrical energy into mechanical motion and transfers it to the car, which in turn either transfers it to the air or transforms it into heat at the bearings.

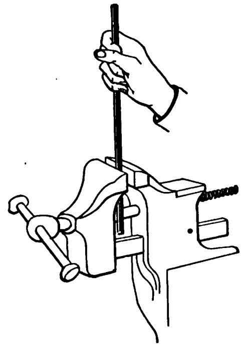


FIG. 149. — The hand when bending the wire does work. Heat is produced.

THE MEASUREMENT OF WORK AND ENERGY

74. **The Relation of Work to Force and Distance.** — The amount of work done by a man when lifting a load depends upon two things: (1) the weight of the load, and (2) the vertical distance through which he lifts this load. But the weight of the load is the force with which the man acts in the vertical direction, hence, the two things upon which the amount of the work depends are (1) *the force*, and (2) *the distance* the load moves in the direction of that force (Fig. 150). Similarly the amount of work done by an engine in moving a train depends upon (1) the force with which the engine acts upon the train, and (2) the distance the train moves in the direction of that force. In general the number of units of work equals the number of units of force multiplied by the number of units of distance, or $w = fd$.

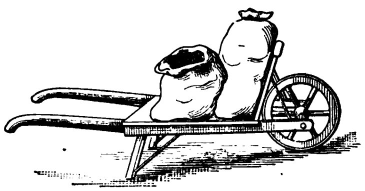


FIG. 150. — The work done by a man in moving the wheelbarrow depends upon the force with which he must push horizontally and the distance he moves the load in that direction.

75. **Units of Work. The Erg, the Foot Pound, and the Kilogrammeter.** — Since amount of work depends upon both force and distance, the most convenient unit of work and energy will be *the work done or energy given by any agent which acts with a unit force through a unit distance.* If any body *acts with the force of* 1 *dyne through a distance of* 1 *cm.* the work done or the energy given is called 1 *erg.* This, the simplest unit of work, has the same value everywhere, but it is very small. As stated, the earth acts with a force of 980 dynes on a gram mass, at New York, hence when we lift a gram 1 cm. we do 980 ergs of work; and to lift a "nickel," weighing 5 gm., from the floor to a table 100 cm. high would require $980 \times 100 \times 5 = 490{,}000$ ergs. Because the erg is so small engineers commonly use another unit equal to **10,000,000 ergs.**

This unit is named 1 *joule,* in honor of James Prescott Joule, of England.

Units of work more convenient than the erg may be formulated by using the gravitational units of force such as the pound and kilogram. For example, if one's hand acts upon a piece of iron weighing 1 lb. and moves it vertically upward a distance of 1 ft., the work done or the energy imparted by the hand is called a *foot pound.* More generally then *whenever any body acts upon another in any direction with the force of one pound and moves it one foot in that direction the work done or energy transferred is called one foot pound.* The work done by any agent may then be found by multiplying the number of pounds with which the agent acts by the number of feet through which it moves the load.

Briefly, no. foot pounds = no. pounds × no. feet.

Thus, the work done by a horse in moving a wagon along a street may be calculated by finding the average number of pounds with which he pulls and the number of feet the wagon is moved in the direction of his pull. For example, when his pull is found to average 460 lb., the work done in moving the wagon 1000 ft. will be $1000 \times 460 = 460{,}000$ ft. lb.

If in measuring work we select the kilogram as the unit of force and the meter as the unit of distance, then the work done by any agent in lifting a body weighing one kilogram through a vertical distance of one meter will be the *unit of work or energy,* called a *kilogrammeter.* More generally the number of kilogrammeters of work done by any agent can be found by multiplying the number of kilograms with which the agent acts by the number of meters through which it moves the load in the direction of the action.

No. kilogrammeters = no. kilograms × no. meters.

We may also define a unit of work in terms of the gram and the centimeter as our units of force and distance. The

unit thus obtained is called the gram centimeter of work. (In defining units of work as given above, we generally select the case of the work done in lifting bodies simply because they furnish the best examples of a practically constant force.)

Because a pound, a kilogram, or any other gravitational unit of force is not strictly the same everywhere, foot pounds and kilogrammeters do not have quite the same value at all places. For the most exact calculations, then, the work done by a body should be computed in ergs or joules.

How to compute Kinetic Energy. — When a body is in motion, the energy which it has may be found in one of two ways:

(1) We may find with what force and through what distance an agent would have to act to supply the amount of energy possessed.

(2) We may find with what force and through what distance the moving body must act to give up all its energy.

The general equation $f = ma$ (sec. 59), expresses the relation between the force, the mass, and the acceleration, when a body is acted upon by one agent only, and the equation $d = \frac{1}{2} at^2$ gives us the distance passed over in time t, for the same conditions. But the work done is $w = fd$; hence, in this case the work, $w, = ma \times \frac{1}{2} at^2 = \frac{ma^2t^2}{2}$; but for a moving body it can be assumed that we know only the mass and the velocity. Hence, we must substitute for a^2t^2 its value in terms of v.

By an equation in section 56, $v = at$, hence $v^2 = a^2t^2$.

Substituting in the above equation, the energy required to give the body the velocity it really has or the energy which may be given out by the body in coming to rest, is equal to $\frac{mv^2}{2}$. Hence, the kinetic energy of a body, $e = \frac{1}{2} mv^2$.

In most cases it is more convenient to use the weight of a body in making the calculations for kinetic energy instead of the mass. In such cases we substitute for m its value as given in the equation $wt = mg$ or $m = \frac{wt}{g}$. When substituted, we get as the equation for kinetic energy $e = \frac{wtv^2}{2\,g}$.

How to compute Potential Energy. — Since potential energy is unknown as to its nature, the only way in which we can compute the quantity of potential energy is to determine, in each case, either how much work is done in producing the potential energy, or how much work can be done by the body which is considered to have the poten-

tial energy. Thus the amount of energy given to the spring in a window shade can be found if we know the force and the distance through which a body must act in giving it this energy as already shown in the preceding paragraph. When the spring stops in any position, the potential energy is either the energy required to put it into this position or the work which the spring will do in returning to its original position. Similarly, after a stone is lifted, the amount of potential energy represented is either the amount of work done in putting it into this new position, or the amount of kinetic energy developed in letting it fall to the original position. Since the original and final positions of both spring and stone are purely relative, it follows that there is a possibility of getting a variety of answers to a problem of this kind unless the points of reference are definitely stated or plainly understood.

Questions and Problems

1. How much work is done in lifting a book weighing 2 lb. from the floor to the top of a table 3 ft. high? How much work is done in lifting 200 gm. through the same distance?

2. While the book is on its way up, which type of energy is being produced? From what type is it being produced? After it is on the table, what name do you give to its energy? Why? How can you prove your right to say that it has energy when at rest on the table?

3. Is driving a nail doing work? If so, what two things must be known to find the amount of work done each time the nail is struck?

4. Could a workman give more kinetic energy to a hammer when striking a downward or a horizontal blow? Why?

5. A man weighing 140 lb. does how much work in lifting his own body when he walks from the first up to the third floor of a building, each floor being 12 ft. higher than the one next below it? How much additional work would he have to do if he carries a box weighing 25 lb.?

6. A trunk weighs 100 lb. and a boy's express wagon 50 lb.; how much work must be done to lift both of them 7 ft. vertically? If the boy pulls the express wagon and the trunk along a level street, does he do the same amount of work per foot as when he lifts them vertically? What two quantities would you have to know to find the work that the boy does in hauling the trunk from one street corner to the next?

7. How much work is done in lifting 3 cu. ft. of water 1 yd. vertically? Would the necessary quantity of work be increased or decreased by lifting the water in a slanting direction provided the water is raised 1 yd. higher than it was at first?

8. When is work or energy said to be wasted? When is energy said to be transformed?

9. A baggage man is pushing a loaded truck (Fig. 151) up a sloping platform which rises 1 ft. for every 12 ft. of its length. How much work does he do in moving the truck and load weighing 1000 lb. along the whole platform, a distance of 60 ft.? Does the arrangement of the given load of trunks affect the amount he must lift at the handles H, H? Does it affect the amount of work he must do?

10. By the use of a kind of spring balance called a *dynamometer* it is shown that a horse in moving a wagon pulls 400 lb. on a level street and 650 lb. on a certain hill. Find how much work the horse does when moving the wagon 1 yd. (*a*) on the level street, and (*b*) on the hill.

11. When a man is winding his watch, to what type does the energy of his hand belong? After the winding is finished, what name do you give to the energy of the spring? Why?

12. When the exploding powder acts upon a bullet in a gun, what two things should we have to know to compute directly the work done upon the bullet? If the bullet were shot vertically upward, what two things must be known to compute its energy? Would its energy at the instant it stops rising be kinetic or potential? Which type of energy does it have at the instant it leaves the gun? What two things are required in order to find the energy at the instant it leaves the muzzle of the gun?

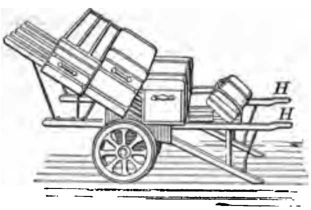


Fig. 151.

13. How much energy has a body weighing 20 lb. when moving with a speed of 8 ft. per second? One weighing 250 gm. moving with a velocity of 60 cm. per second?

14. In what position does a vibrating pendulum have the most kinetic energy? the most potential? When at rest, considered as a pendulum, which kind is it said to have? which kind when it is considered as a body elevated above the floor?

15. Explain why the amount of energy a body is said to have at any time does not depend upon that body alone.

16. In computing the potential energy of an elevated body, if the point of reference is not stated or plainly indicated, what point do we select?

17. Find the potential energy of 800 gm. when lifted 1500 cm. above the surface of the earth. If allowed to fall, what amount of kinetic energy will it possess when it strikes the earth (no allowance being made for wasted work)? With what velocity will it be moving when it strikes?

18. Does a pound force have the same value everywhere? Does a dyne? Does a foot pound? Does an erg? Give your reason in each case.

76. Power or Activity; Time Rate of doing Work. The Horse Power. The Watt. — The work which is done by any agent may be calculated, as just shown, without reference to the time required to do it. Time, however, is always required for the transfer or the transformation of energy, that is, the doing of work. Every man, horse, engine, or motor is limited in respect to the amount of energy each can furnish in 1 sec. If we compute the amount of work which any agent can do in a unit of time, we have determined its *power or activity.* Briefly, *the power of an agent is its time rate of doing work.*

The Horse Power. — An agent which can do 550 ft. lb. of work in 1 sec. is said to have 1 *horse power.* Based as it is on the pound and foot, a horse power is called the English unit of power. For reasons given its value is not exactly the same everywhere. In estimating the power of various agents, such as animals, engines, motors, it is customary to consider the greatest power that the agent can exhibit for a considerable time as the true measure of its power. Hence, a 10 horse power engine can do 5500 ft. lb. or any number less than 5500 ft. lb. per second. A knowledge of power is of value chiefly in connection with those agents which, like animals, steam engines, and motors, *transform* energy either from the potential to the kinetic type, or from one of the kinetic forms into another, as, for example, heat into mechanical energy.

The Watt. — A more exact unit of power is based upon the erg as a unit of work. An agent which can do 1 joule (10,000,000 ergs) of work per second is said to have a power of 1 *watt,* a name given in honor of James Watt, the distinguished Englishman who made most important improvements in the steam engine. A watt is about $\frac{1}{746}$ of a horse power. A power of 1000 watts is called 1 *kilowatt.* It is equal to about $1\frac{1}{3}$ horse power.

77. The Conservation and Correlation of Energy. — In our discussions hitherto concerning the transferring and trans-

forming of energy, we have assumed that in all these changes the total quantity of energy involved could suffer no change—in brief, we believe *that energy cannot by any process be created or destroyed.* This general statement concerning energy is known as the Principle of the Conservation of Energy. This principle, like all other great generalizations, can be proved by no single experiment. It is an induction which was the outgrowth of years of patient toil on the part of many of the world's greatest investigators. We shall see the evidence of its truth accumulating as our knowledge of physics broadens.

Since energy can neither be increased nor decreased in its amount by any transformation it may undergo, it follows that there must be a definite quantity of each kind of energy which is always equivalent to an equally definite quantity of each of the other kinds. This important truth is known as the doctrine of the *Correlation of Energy.*

78. **Useful Work and Wasted Work.** — In performing the physical work of the world we generally have in mind a definite result which we are seeking to accomplish. For example, if an engine is lifting a stone to the top of a wall, the end sought is plain and the amount of work which must be done upon the stone can be readily computed from certain easily determined facts. But it is well known that in lifting the stone the engine must put in motion other things, such as the surrounding air; and it will generate more or less heat also at its own bearings as well as at those of the pulleys and other mechanism used. In short, the engine must supply a quantity of energy or do an amount of work besides that which is directly desired. The work which is done upon the load is called *useful work*, but that which is done upon other objects or, in other words, *that energy which does not go to the desired use is called wasted work or wasted energy.* In a similar manner there is wasted work in using steam engines, dynamos, and motors, which *transform* one kind of energy into another. The

best of such machines transform only a part of the original kind of energy into the kind desired. Thus a steam engine may waste 90 or 95 per cent of the heat energy furnished by burning the fuel. Good construction and the intelligent operation of any machine add materially to the *percentage of useful work* called the *efficiency* of the machine. This suggests that there is an economy of energy which is quite as profitable as an economy of material in conducting the mechanical affairs of the world.

Perpetual Motion. — Since in the running of all mechanisms there is a waste of energy at the bearings and to the air, it follows that the dream of constructing a machine which, when once set in motion, would continue moving forever cannot in the nature of things be realized. Perpetual motion under ideal conditions is possible in the sense that it is not contradictory to the nature of motion and energy, but it is absolutely impracticable to make a perpetually moving machine, for all machines on account of their weight are compelled to waste energy at their bearings. To keep such a machine going uniformly energy from some source must be supplied at exactly the same rate as that at which the loss occurs. Only under purely ideal conditions could perpetual motion exist.

Questions and Problems

1. How much work is required to carry 1000 bricks, each weighing 8 lb., to the top of a wall 20 ft. high? Working at their best, A can take them to the top in 40 min., but another man B requires 1 hr. How do the amounts of work compare? How do their rates of doing work compare? Which man has more power? Why?

2. How much work can a 4 horse power engine do in 1 min.? in 3 hr.?

3. In what time could a 2 horse power engine lift the bricks of problem 1 to the top of the wall?

4. A city requires 10,000 cu. ft. of water per hour. If the vertical distance from the river to the reservoir is 60 ft., find what horse power engine is required to pump the water — wasted work being neglected.

5. How many ergs of work are done when 1 gm. is lifted 4 cm.? One joule is equivalent to how many ergs? Define a watt.

6. How much work can a 10 kilowatt engine do in 15 min.? How many horse power would such an engine have?

7. In problem 9, page 128, where does the wasted work appear? Oiling the axles has what effect upon the quantity of wasted work?

What effect upon the useful work? Express in terms of work the advantage of ball bearings in a bicycle.

8. From the standpoint of work and energy explain why it pays to have public highways and railways well graded and smooth.

9. Why cannot a body do work upon itself? Can one part of a body do work upon another part of the same body? Give an example and prove that the parts are, for the time being, two distinct bodies.

79. Newton's Laws of Motion and their Relation to Energy and Work. — The fundamental laws concerning the motion of bodies were first stated by Sir Isaac Newton and are commonly known as Newton's Laws. They may be stated as follows:

First: Every body continues in its state of rest or of uniform motion in a straight line, unless compelled by force to change that state.

Second: Change of momentum is proportional to the force acting and takes place in the direction in which the force acts.

Third: To every action there is always an equal and contrary reaction; or the mutual actions of any two bodies are always equal and oppositely directed.

When these laws were first stated by Newton, the ideas of work and energy were very imperfectly developed and the terms themselves not in use.

No direct and complete demonstration of these laws is possible, though evidence of their truth is found in the motions of all bodies. The most convincing evidence is found in the accuracy with which astronomers, by their aid, can predict the motions of the heavenly bodies.

80. Interpretation of Newton's Laws. — The first law is frequently called the *law of inertia.* The term *inertia* as here used is intended to express the fact that a body cannot create or destroy its own energy. If a body at rest could set itself in motion, it would be creating kinetic energy. Likewise if a body in motion could stop itself, it would be destroying energy. The energy of a body must remain the same in

all respects, unless by the action between it and a second body there is some change produced in the energy of each. Thinking of a body as stubbornly resisting a gain or a loss of motion, that is, as resisting an energy change, gives one a false notion of the relation of matter to energy.

The following illustration may help to form the correct notion. Let us suppose that a tank contains no water, it must remain without water until some external source (rain, river, etc.) furnishes a supply. The tank cannot create water and fill itself. On the other hand, if full it will continue to contain water until all the water is removed by some process (leakage, evaporation, pipes, etc.). That is, the tank cannot destroy or convert water into nothing and thus empty itself. This is no evidence of stubbornness or laziness on the part of the tank, but is due entirely to the indestructibility or the conservation of matter.

Similarly the so-called inertia of matter is a necessary outgrowth of the conservation of energy.

Applications of Newton's First Law.—The bottom sheet in a pile of paper may be withdrawn by a sudden jerk without appreciably moving the rest of the sheets (Fig. 152). This shows the so-called inertia of the upper layers of paper. It takes time to give energy, and the moving sheet is acting for so short a time that little energy is given to the sheets above before the first has gone entirely out of the pile. Move the bottom sheet less and less quickly, and the ones above get more and more motion or energy before the bottom one gets away. If we increase the friction between them by the use of fine sand, from the first it may be impossible to withdraw the bottom sheet without moving or greatly disturbing the pile. A tank fills quickly when its capacity is small or when the time rate of flow of the water is large. A body acquires a high speed quickly (1) when its mass is small, (2) when the time rate at which it gets energy is large. On the other hand, a body acquires motion slowly (1) when its mass is large, or (2) when the time rate at which the energy is supplied

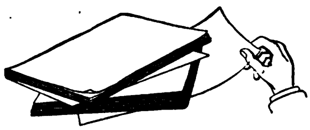


FIG. 152.—Showing inertia.

is small. A passenger standing in a moving car may continue to move when the car suddenly stops. His feet in contact with the floor lose motion or energy, and he may lose his balance because his body continues to move. Similarly, when the car starts, motion is given first to the feet of the standing passenger, and, if the car gains speed rapidly, before the rest of his body can be set in motion his feet are literally pulled from under him and he again loses his balance, this time falling backward. In a similar way any two bodies may be separated by quickly giving to or withdrawing motion or energy from one of them (Fig. 153). Beating a carpet and kicking snow or mud from one's shoes are familiar examples. The first law of motion, then, is the outgrowth of the nature of energy. In all cases where bodies seem to move or stop themselves, like the case of a coiled spring jumping when released, or that of an animal running, or a rising body stopping, etc., it will be found that the energy of motion is being produced from or converted into potential energy by the action between the given body and some other, or by the action between its parts.

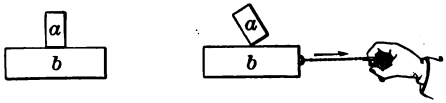


FIG. 153. — Inertia. If b is put into motion quickly, the lower part of a receives motion before its top does.

81. Second Law of Motion. — This law means that when any body acts upon another, first, the *quantity* of motion produced in a unit of time depends alone upon the magnitude of the action or force, and, second, the direction of the motion produced is the same as the direction of the force with which the body acts. A locomotive commonly produces motion of the car in the direction in which it acts, and if the mass of the car is fixed the momentum (mass × velocity) produced per second depends entirely upon the force with which the locomotive acts. This produced momentum may add to or subtract from any previous momentum of the car, depending upon its direction as related to that of the original momentum.

When a body does not move in the direction of the force, it will be found that there is more than one body acting upon the body in question (Fig. 154). For example, a ball lying on the table may move *horizontally* when struck *nearly vertically* by a mallet. The table and the mallet both act upon the ball, and the motion observed is the result of their joint action. The force of the mallet may be resolved into two forces, one perpendicular to the table and one parallel to it. This last is the force in the direction of motion, and the amount of momentum produced varies as this force.

82. Third Law of Motion. — The word *action* as used in this law must not be confused with motion. Action means here what it has already been used to indicate in connection with the term *force*. A book weighing 1 lb. lying on the table is said to act upon the table with a force of 1 lb. The table also acts upward upon the book with a force of 1 lb. Neither moves. This action between the table and the book may be spoken of as either the *action* of the book upon the table or the *reaction* of the table upon the book. All action involves at least two bodies. The one may be said to act and the other to receive the action. In many cases we may call either body the actor. Clap your hands. Hold one hand and strike it with the other. Drive a nail with a wooden mallet. The effects on the hands and mallet show that the process called striking involves two bodies, and the force of striking is the same whether measured from the standpoint of the one or the other body (Fig. 155). Action and reaction are really two different names for the same process — an energy transaction.

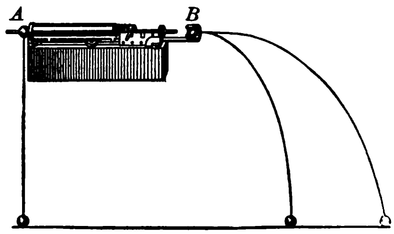


FIG. 154. — Newton's second law of motion. The ball *B*, though shot horizontally, falls as fast as *A*.

Illustration. — A man goes into a store and ***buys a hat.*** **Speaking** of the same transaction, the merchant says he ***sells a hat.*** **The two** men have different points of view of the same action, — a business transaction, — hence use different words in describing this transfer of property.

Since the attraction between two bodies, as a magnet and a nail, is an example of action, here too the action and reaction are equal. It follows that if the attraction from the standpoint of the magnet is 1 gm., it must also be 1 gm. from the standpoint of the nail. Likewise the attraction between the earth and a book is the same amount, whether we think of it from the point of view of the earth pulling the book, or the book pulling the earth.

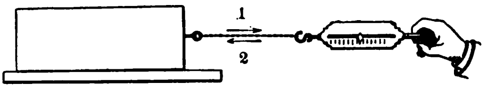


FIG. 155. — The third law of motion. The spring balance measures the pull of the hand in direction 1 and also the pull of the block in direction 2.

A simple demonstration of this may be given by using two balls suspended from the ceiling as shown in Figure 111 with a rubber band stretched between them. The band pulls equally on each, but when released the smaller mass moves faster. Similarly, when a book falls the earth moves toward it, — so little, of course, that it could not possibly be noticed, — for the force upon the earth urging it toward the book is equal to that which urges the book toward the earth.

QUESTIONS AND PROBLEMS

1. The angular velocity of the earth is constant. Is this an evidence that some other body is acting upon it as a whole? Is it evidence that there is some action or attraction between its parts? Why?

2. The earth moves in a curved path around the sun. Is this evidence of the action of some body upon it? Why?

3. Why cannot a person lift himself by taking hold of the chair on which he is seated?

4. Explain the removal of snow or mud by kicking the shoe against a stone.

VII. MACHINES

83. The General Purpose of Machines. — It has already been shown that essentially all the changes which occur in the material world consist in the moving of bodies. The processes involved in the operation of farms, railroads, and factories, even where chemical processes like burning are involved, create and destroy no material, they are all concerned with the motion of bodies in a great variety of ways; consequently, we may say that all these processes are only different ways of doing work. Human power, even when there is no disposition to save it, is unable to do all the useful work of the world. In order to accomplish in a given time a *quantity of work* far beyond the power of man, or to move bodies when the *force* required is greater than man can directly exert, or when the *speed* desired is greater than he can directly produce, it is necessary to use various devices, called *machines*. Familiar examples of these machines are windmills, water wheels, levers, and pulleys, which *transfer* kinetic energy from one place or object to another; the steam engine, the motor, and the dynamo, which *transform* or change energy from one of its kinds into another. From the results accomplished by these machines, it is evident that *the general purpose of a machine in the broadest sense may be either to transfer or to transform energy.*

84. The Simple Machines; General Laws. — There are six particular devices, called the *simple machines*, which are used only to *transfer energy.* They are known as the *lever,* the *pulley,* the *wheel and axle,* the *inclined plane,* the *screw,* and the *wedge.*

We must think of these *simple machines* as bodies that stand between the body that does the work and the one upon which the work is finally done; they are *not sources of energy.* Thus when a horse lifts a stone by means of a pulley, the horse is the body which should be credited with the work on the stone and the pulley is the intermediate machine.

Throughout our discussion of the simple machines, as heretofore, we shall call the *body that does the work or furnishes the energy the actor or agent,* and the *one which finally receives the energy, the load.*[1] It must be kept in mind that the simple machines are intended primarily *to move* bodies, not merely to balance them, as is so frequently the case in our laboratory and other experiments.

Recalling the principle of the conservation of energy, which asserts that energy cannot be created or destroyed, it follows:

1. A simple machine can give to the load no more energy than it has received from the agent.

2. A simple machine must give to the load or something else all the energy it receives from the agent.

3. That part of the energy which a machine receives and does not give to the load is called *lost* or *wasted energy.* It is called wasted work or energy, because it does not go to the desired use. Only an ideal machine could transmit to the load all the energy that is furnished by the agent. All working machines waste energy. The chief cause of waste is the generation of heat at the bearings of the machine. The general principles may be summed up as follows:

[1] In connection with machines the agent has often been called the *power* and the load expressed as a *weight,* — but since the word *power* has another meaning in physics, and because the load is often not a *weight,* confusion results from the use of these terms instead of those suggested above. The terms *effort* and *resistance* are suggested by some writers instead of the terms *agent* and *load.* Though offering a decided improvement on the terms power and weight, this use of the terms effort and resistance is objectionable because it demands that the same terms shall at one time express a force and at another time a material body.

work done by agent = *work done upon load* + *waste.*

But *work done* = *force* × *distance.*

Hence *force of agent* × *distance agent moves* =

force on load × *distance load moves* + *waste,*

or $F_a \times D_a = F_l \times D_l + waste.$

85. The Efficiency of a Machine; Mechanical Advantage. — In many problems the wasted energy is neglected, but in the actual working of machines, wasted energy is always involved, frequently constituting a large part of the total work done by the agent. The energy given by the machine to the load, *useful work,* divided by the work done by the agent is called the *efficiency of the machine.* $Efficiency = \frac{work\ on\ load}{work\ of\ agent}.$ It is usually expressed as a decimal or given as a per cent. For example, when we say a set of pulleys has an efficiency of .9 or 90 per cent, we mean that the load receives .9 or 90 per cent of the energy furnished by the agent; the rest is wasted in moving the surrounding air and in the generation of heat, etc.

The securing of any end sought is called an advantage. It can be shown by experiments that in the use of the simple machines there may be secured a change (1) in force, (2) in distance, (3) in direction of motion, or (4) in speed of the load as related to the agent. Securing any of these changes when desired is called a mechanical advantage, though there is commonly a loss in another respect. Thus, if we so arrange a lever that the force at the load is three times the force at the agent, we have a mechanical advantage of 3, in so far as force is concerned, though there has been a corresponding loss in the distance through which the load moves.

Questions

1. When is a machine said to furnish a gain in force? When a gain in speed? When a change in direction? In which cases is there

a corresponding loss? In which cases is there a mechanical advantage? Why do you call it an advantage?

2. Are simple machines intended to transmit or transform energy? State the difference between the two processes.

3. Give a reason why a simple machine cannot do more work per minute upon the load than is performed by the agent upon the machine.

4. Prove that the power of a man or engine cannot be increased by the use of a simple machine. Show that force or speed may be thus increased or decreased.

5. Distinguish between the useful and wasted work of a machine. State two reasons why it pays to oil axles and other bearings of machines.

86. The Lever. — A bar of wood or other rigid body so arranged as to enable a person or other agent to move something with it, is a lever (Fig. 156). Besides the lever there are three other bodies involved, — the *agent* (A), the *load* (L), and the body around which the lever turns, — called the *fulcrum* (F).

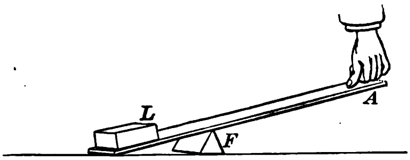


FIG. 156. — A simple lever.

Each of these three bodies acts upon the lever, but since the fulcrum receives or should receive none of the motion, we may in many calculations omit its consideration, though we must not forget its importance. Since all three bodies act upon the lever, there is a *force* at each point of action.

The Classes of Levers. — The distance from the axis or place where the fulcrum acts measured perpendicular to the line along which the agent acts is called the *arm of the agent*, and the distance from the axis measured perpendicularly to the line of action on the load is called *the load arm.* In Figure 157 the agent arm is OA, and the load arm is OB. Only

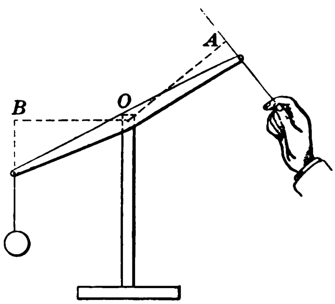


FIG. 157.

when both agent and load act perpendicular to a straight lever are their arms measured on the lever (Fig. 158).

The three bodies, agent, fulcrum, and load, may be differently arranged relative to each other, thus giving us the three so-called classes of levers.

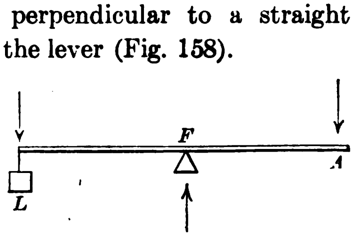


FIG. 158. — A lever of the first class.

First Class: When the fulcrum is between agent and load.
Second Class: When the load is between agent and fulcrum.
Third Class: When the agent is between fulcrum and load.

The classification of levers is intended for convenience merely, and does not indicate any great difference in the mechanical principles involved.

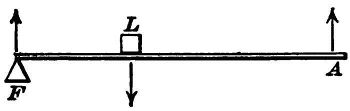


FIG. 159. — A lever of the second class.

The three classes of levers are shown in order in Figures 158, 159, and 160, where the load is a weight (L) and the agent any body (A) acting in the direction of the arrows. The direction of the forces at the load and fulcrum are also marked. Notice that in all cases the two outer forces have the same direction opposite to that of the force between. (See Principle of Moments, sec. 66.)

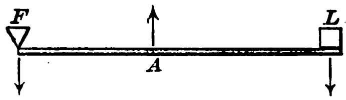


FIG. 160. — A lever of the third class.

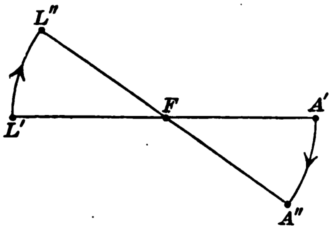


FIG. 161. — A change in direction of motion only.

87. The Advantages afforded by Levers. *First Class of Levers; the Fulcrum between the Agent and Load.* — Let us suppose that, as shown in Figure 161, the agent moves from A' to A'', while the load is moving from L' to L''. The general direction

of the agent has been downward, while that of the load has been upward. Thus, because the load moves in a direction different from that of the agent, we have, by the use of the lever, secured a *change in the direction* of motion. Neglecting the wasted work, as we must do in discussing the general cases, there is in this instance no change in force or distance, for since $A'F = L'F$, and by the principle of moments (sec. 66), force $A \times A'F =$ force $L \times L'F$, it follows that force $A =$force L. But in the arrangement of Figure 162, arm $L'F$ is small compared to $A'F$, hence the force on L is large compared to force at A. Since the agent arm $A'F$ may be made as many times the length of the load arm FL' as desired, it follows that the load force may be made as many times the agent force as we may wish. By using the lever in this way we have secured both a change in direction and a gain in force. It must be noted that accompanying this *gain in force* there is a corresponding *loss in distance*, or, since agent and load start and stop together, there is *a loss in speed.*

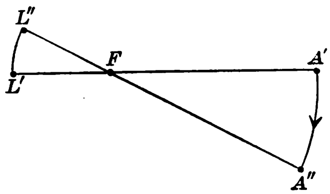


FIG. 162. — A change in direction and a gain in force.

Force may, therefore, be increased or decreased by the use of a lever, but, as already shown, the amount of energy cannot be thus changed. This is one of the most satisfactory proofs that force and energy are different.

If in Figure 162 the agent and load were to exchange places, it is evident that there would be a loss in force, but a corresponding gain in distance and speed.

Briefly, then, a lever of the first class may secure:

1. A change in the direction of motion.

2. A gain in force with a consequent loss in distance and speed.

3. A gain in distance and speed with a consequent loss in force.

Second Class of Levers; the Load between the Fulcrum and Agent. — A lever of the second class is represented in Figure 163, the load being between the fulcrum and agent.

The load and agent being on the same side of the fulcrum, no change in direction can now be secured, but since the agent arm is necessarily longer than the load arm, with the second class of lever there is always a gain in force and a loss in distance and speed.

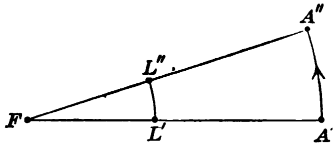


FIG. 163. — A gain in force with a loss in distance and speed.

Third Class of Levers; the Agent between the Fulcrum and Load. — When the agent is placed between the load and the fulcrum, as in a lever of the third class (Fig. 164), there is always a loss in force with a corresponding gain in distance and speed, but no change in the direction of motion.

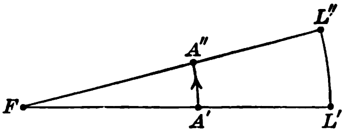


FIG. 164. — A gain in distance and speed with a loss in force.

The Effect of the Weight of the Lever. — In the discussion of the classes of the lever we have assumed that the three bodies, agent, load, and fulcrum, all act at points and along lines at right angles to the lever, and we have neglected the weight of the bar or lever. In the use of a lever as a practical machine, the agent and load rarely act at single points, and the lever always has weight. In such cases a solution can generally be found by first selecting a point at which each body may be regarded as acting, and then treating the weight of the lever as a single force located at its center of gravity.

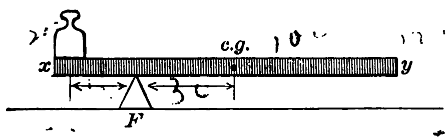


FIG. 165. — The weight of the bar acts as if it were all located at the center of gravity.

For example, if the bar xy (Fig. 165) is 100 cm. long and

weighs 1200 gm., its center of gravity may be considered as being at a point 50 cm. from either end. If F is placed 30 cm. from this center of gravity, the weight of the bar alone would produce a positive moment of 30 (arm) × 1200 (force) = 36,000 units of moment. To balance this moment, a load is placed on the end of the bar at x. If the center of gravity of the load is 18 cm. from the axis, then 3600 ÷ 18 (arm) = 2000 gm., the force required to balance the lever alone. It is plain then that any agent at y would have assistance from the weight of the lever in moving any load placed between F and x.

The Application of Levers. — The lever principle, that is, the principle of moments, is used in nearly all kinds of weighing devices, excepting where springs are used — the spring balance. Sometimes the arms are equal, or again one arm is much longer than the other (Fig. 129). Since weighing is balancing, we cannot in this case distinguish between agent and load, but rather speak of the bodies as two loads that are inversely proportional to the two arms of the lever used. Since most experimenting on levers consists in balancing forces, rather than in moving bodies, the student must guard against the conclusion that this is their chief use.

The lever as a simple machine is found as an element in the construction of practically all the more complicated machines, such as engines, sewing machines, bicycles, and the various machines used in factories.

Questions and Problems

1. A bar 28 in. long is supported on an axis running through its center C. If a weight of 40 lb. is placed at one end A, find the magnitude and direction of the force of the agent at the other end B. Find the force if the agent acts at D, a point midway between C and B. Use a drawing.

2. What class of lever is represented in problem 1? Suggest changes in the location of either the load or the agent which would furnish examples of each of the other two classes.

3. State the principle of the conservation of energy and apply it to

the work done by the agent as related to the work done upon the load, in the case of a lever.

4. What effect does the wasted work of a lever have upon the amount of work the agent using the lever must do?

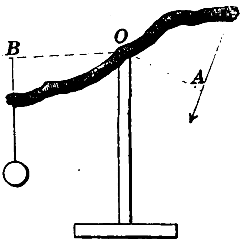


FIG. 166.

5. If the agent acts at A (Fig. 166), is there a gain or loss in force? a gain or loss in speed? Why?

6. A man is moving a load on a wheelbarrow. From the axis of the wheel to the point vertically below the center of gravity of the load is 2 ft.; from this point to each of the man's hands is 3 ft.; the load weighs 225 lb. How much must the man lift, not counting the weight of the wheelbarrow? Make a simple drawing.

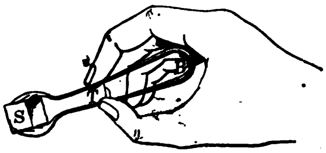


FIG. 167.

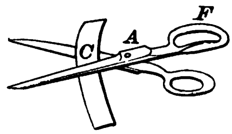


FIG. 168.

7. Will the weight of the wheelbarrow, problem 6, increase or decrease the amount the man must lift? If the barrow, not counting the wheel, weighs 160 lb., and its center of gravity is 1 ft. from the axis, how much does the man lift, including the barrow?

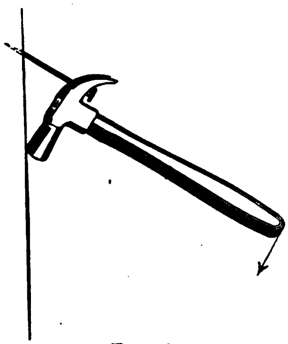


FIG. 169.

8. Find the force at the axle of the wheel or fulcrum (*a*) without counting the weight of the barrow (*b*), including the weight of the barrow.

9. Locate agent, fulcrum, and load in each of the following: sugar tongs (Fig. 167), a pair of scissors when cutting (Fig. 168), a claw hammer when drawing a nail (Fig. 169).

10. Examine a piano or typewriter and locate the agent and the load (the hammers, or type). Observe the motion and determine whether there is a gain in force or speed. Make a similar observation on a nut cracker (Fig. 170).

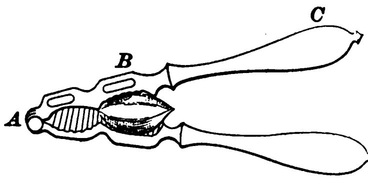


FIG. 170 — A nut cracker.

11. When a nail is being drawn by a claw hammer (Fig. 169), which is greater, the work done by the hand at the handle of the hammer or that done by the hammer upon the nail? Why? If the handle is grasped nearer to the head of the hammer, how will that affect the force required at the hand? the force on the nail? the work that must be done at the hand? the work on the nail? Would a change in the direction in which the hand pulls affect the force necessary? Would it change the useful work? the wasted work? Why?

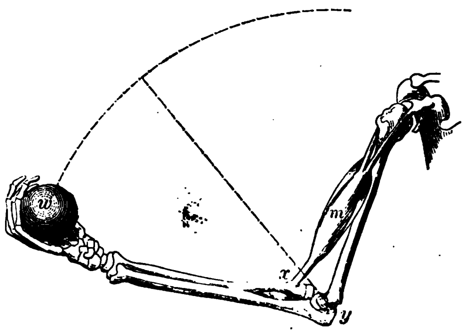


FIG. 171.

12. A plank, 16 ft. long, weighing 40 lb., is used for a seesaw. If one child, A, weigh 50 lb. and the other, B, 30 lb., find how the children might be placed so as to balance each other when the plank rests as nearly as possible at its center of gravity. If one child is placed at each end, find how the plank must be placed on the support so that they will then balance each other.

13. The forearm is moved by the contraction of a muscle, m (Fig. 171). What kind of a machine is it? Where is the axis? At what point does the agent act? What is the relation between the force on the load and the force of the agent? What is gained? Compare the work done by the muscle with the work done upon the load in the hand.

88. The Pulley. — The pulley is a short cylinder or wheel, with a grooved circumference, mounted on an axle. When a cord is passed part way around the circumference of the pulley, as shown in Figure 172, the pulley, like the lever, may be acted upon by three bodies, one at each end of the cord and one at the axle, or the frame attached to it.

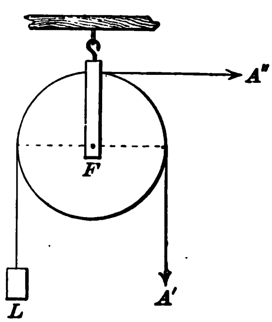


FIG. 172. — **A fixed pulley. The agent and load move in different directions.**

Returning to our idea of agent, load, and fulcrum, we may say that the agent acts at A' or A'', the load at L, and the

fulcrum at F. A pulley used in this manner is then virtually a lever of the first class with the two arms equal, both being radii of the same circle. Since the arms are equal, there is the same force, distance, and speed at the load as at the agent, but the load always moves in a direction different from that in which the agent moves; hence, this pulley secures a *change in direction* only. When arranged in this way the pulley does not move with the load, and on that account it is called a *fixed* pulley.

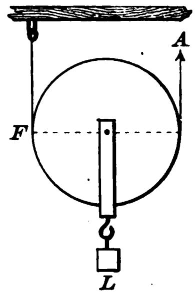


FIG. 173. — A movable pulley furnishes a gain in force, but a loss in speed.

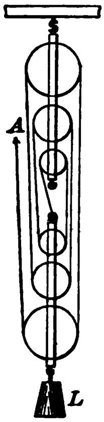


FIG. 174.

Let us now use one end of the cord as the fulcrum F, as shown in Figure 173, having the load act at the axle or in a line through it, and the agent at the other end of the cord.

This is virtually a lever of the second class with the agent arm (diameter of pulley) twice as long as the load arm (radius of pulley). Hence the force on the load will be twice the force of the agent, the weight of the cord and pulley being neglected, but the distance the load moves and the speed of the load are each only one half the distance and speed of the agent. It must be noticed, however, that a pulley used in this way *moves with the load L*, and for this reason it is called a *movable pulley*. We see that a single fixed pulley changes direction of motion only, and a single movable pulley changes force only.

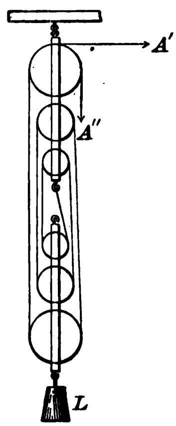


FIG. 175.

By using a combination of two or more of both types of pulleys, we can change direction and force to any desired extent. As shown in Figure 174, the force of the agent is $\frac{1}{6}$ of the force on the load, but when used as in Figure 175, the force of the agent is $\frac{1}{7}$ of

the force on the load, the difference between the two cases depending upon the location of the fixed end of the cord.

Questions and Problems

1. A load is attached to one end of a cord passing over a single fixed pulley. What is the relation between the speed of the load and that of the agent attached to the other end of the cord? What is the advantage of using a single pulley used in this way?

2. One end of a cord is attached to a horizontal bar. The other end of the cord is then passed around a single pulley which is attached to a load. Which is greater, the force at the load or the force of the agent attached to the free end of the cord? Which is greater, the distance the agent moves or the distance the load moves? Compare the product of the force and distance of the agent with the product of the force and distance on the load.

3. One end of a cord is attached to the frame of a fixed pulley; the cord is then passed over a movable pulley, and afterward over a fixed pulley. Make a drawing of the combination of pulleys and the cord. Make a drawing of a similar combination of two pulleys with one end of the cord attached to the frame of the movable pulley.

4. In each of the combinations of problem 3, find the ratio of the force of the agent to the force on the load. Assuming that the force of the agent in each case is 15 lb., find the work done in lifting each load 8 ft. Will the wasted work increase or decrease each of the calculated results? Why?

5. If one end of a cord is attached to the frame of a set of movable pulleys and the cord is subsequently passed around two pulleys of each kind, find what load could be sustained by a force of 210 gm. at the agent. Solve the problem with the fixed end of the cord attached to the frame of the fixed pulleys.

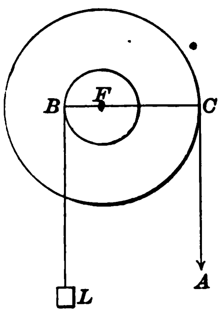


Fig. 176. — The wheel and axle.

89. The Wheel and Axle. — When two wheels of different diameter are firmly attached to each other side by side (Fig. 176), with a common axis F passing through the center of both, we call the arrangement a *wheel and axle*. It must be noticed that this wheel and axle turn together as they do in steam and trolley cars, and not independently as they do in carriages and bicycles.

If one end of a cord is attached to a point in the circumference of the large wheel (Fig. 176), a body acting at the other end, *A*, can balance another acting at *L* on a cord passing in the opposite direction around the small wheel. This arrangement is really a lever of the first class with *CF* the radius of the wheel as the arm of *A*, and *BF* the radius of the axle (small wheel) as the arm of *L*. It secures all the advantages of a lever of the first class.

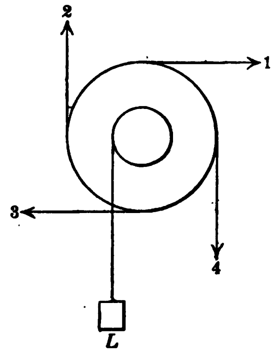


FIG. 177. — The agent may act in any direction tangent to the wheel.

Since all the radii of the wheel are equal, the agent may act in positions 1, 2, 3, or 4 (Fig. 177), and at any one of these positions the force at the load will be as many times the force at the agent as the large radius is times the smaller. In cases 1, 3, and 4, a change in direction is also secured. Exchanging the positions of agent and load will reverse all our conclusions respecting arms, force, distance, and speed.

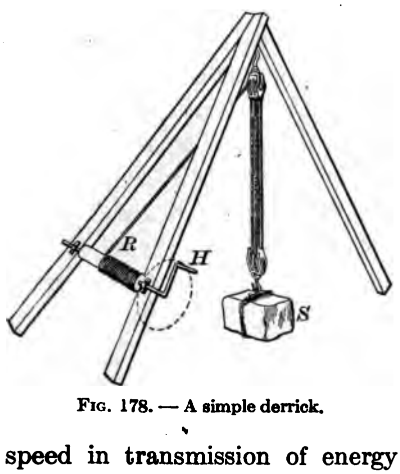


FIG. 178. — A simple derrick.

There are many applications of the wheel and axle, one of the simplest being the common windlass, shown in Figure 178.

One of most important applications is the cog gearing of machinery, used chiefly for the purpose of changing speed in transmission of energy. Clocks and watches have numerous wheels and axles of this kind. A large and a small wheel are frequently connected to each other by means of a

belt or a chain, as in the bicycle. A gain or loss in speed can be secured in this way, depending upon whether the energy is transmitted from a smaller to a larger wheel, or the reverse.

Questions and Problems

1. A wheel has a diameter of 20 cm. and its axle a diameter of 6 cm. If an agent acts upon the cord attached to the wheel with a force of 300 gm., find the force on the load attached to the axle.

2. As the load is moved by the agent, problem 1, which moves faster, load or agent? How many times as fast? How much work is done on the load when it is moved 15 cm.? How does this amount of work compare with that done by the agent? Why?

3. If in a certain windlass (Fig. 178) the diameter of the cylinder *R* on which the rope winds is 9 in., find the length of the crank *H* on which the workman must act in order to pull 480 lb. on the rope *R* with a force of 96 lb. at *H*.

4. If the large sprocket wheel (chain wheel) of a bicycle has a diameter of 30 cm., and the small or rear sprocket wheel has a diameter of 6 cm., which wheel will make more rotations per second? How many times as many? Compare the number of rotations of the rear wheel of a bicycle with the number of rotations of each pedal. Count the number of teeth in each sprocket wheel.

5. Examine a sewing machine, and note whether there is a gain in speed or force in tracing the energy from the foot to the needle.

90. The Inclined Plane. — Any plane surface which is not horizontal (level) or vertical may be called an inclined plane. The upper surface of a smooth board having one end resting on a level table and the other elevated a distance, *NO* (Fig. 179), above it, is an example of an inclined plane. Since the upper surface of the board is parallel to the lower surface, it follows that we may consider *NO* as the elevation of one end of the plane above the other and neglect the thickness of the board. Let the line *MN* (Fig. 180) represent an inclined plane, *NO* the vertical height, and *MO* the base of the plane. Let *L* repre-

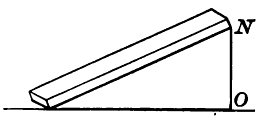


Fig. 179. — An inclined plane

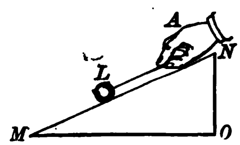


Fig. 180. — *MN* is the length and *NO* the height of the plane.

sent the load, a small cylinder or car, and A the hand or a spring balance, acting parallel to the plane. If we weigh the cylinder L, and measure the force of the hand by means of the spring balance, we find, neglecting friction, that the weight of the cylinder bears the same relation to the force at the hand as the length of the plane does to its height, or

$$\text{force } L : \text{force } A :: MN : NO.$$

Also by the general law of machines (sec. 84) it follows that the weight of L multiplied by distance it is lifted is equal to the force at the hand multiplied by the distance the hand moves, or

$$\text{force } L \times NO = \text{force } A \times MN,$$

hence $$\text{force } L : \text{force A} :: MN : NO,$$

or as shown before,

$$\text{force } L : \text{force } A :: \text{length of plane} : \text{its height}.$$

Since the same relation exists between any portion of the plane MN, and the corresponding height as exists between the whole length of the plane and the whole height, we may, in practice, measure any convenient portion of the plane and its corresponding height.

Various applications of the inclined plane are found in connection with loading and unloading wagons and cars. A stairway is practically an inclined plane with footholds for the person using it. Hills or grades in streets and railways are only inclined planes, and the work done per unit distance by the horse or engine increases for a given load when the ratio of the height to the length of the plane increases.

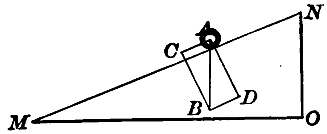


FIG. 181.

Proof of Principle of the Inclined Plane by Resolution of Forces. — Let line AB drawn vertically represent the weight of the body (Fig. 181). This force may be resolved into two forces, one, AD, perpendicular to the plane MN, and having no effect on the motion of the body, and the other

AC, parallel to the plane and representing the force, which must be balanced to prevent the body from moving down the plane. The triangle ABC is similar to triangle NMO, since angle MNO is equal to angle CAB and MON and ABC are both right angles.

From this it follows that the sides of the triangles are proportional, or $AB : AC :: MN : NO$. But the weight of the body is represented by AB and the force to keep it from moving is represented by AC, hence:

$$\text{wt. (load)} : \text{force } A :: MN : NO$$

$$:: \text{length of plane} : \text{height},$$

or

$$\text{wt.} \times \text{height} = \text{force } A \times \text{length of plane.}$$

This means that the work done by the agent equals the work done in lifting the load, waste neglected.

91. The Screw and the Wedge.—If a piece of paper is cut to represent a right-angled triangle and then wound around a pencil as shown in Figure 182, the line of the paper which represents the hypotenuse of the triangle will trace the thread of a screw. This shows that the screw is virtually an inclined plane. Once around the cylinder, measured along the thread or spiral, may represent the length of the plane; and the distance between the consecutive threads will be the corresponding height. The principles of the inclined plane as just explained can now be applied. The familiar screw and nut, the jackscrew (Fig. 183), the so-called spiral or winding stairway, the screw fire escape, are all familiar examples of the application of this form of the inclined plane.

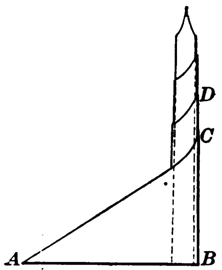


FIG. 182. — $AC : CB$ = cir. on thread: dist. between threads (CD).

FIG. 183. — Screw and nut lifting jack.

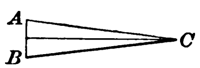


FIG 184. — A wedge.

The wedge (Fig. 184) is another example of an inclined plane, where the plane is usually very long in proportion to its height.

The wedge is usually moved by sudden blows on AB, and hence the determination of the force relations is difficult.

92. The Hydraulic Press as a Machine for doing Work. — The principle of the hydraulic press has already been studied (sec. 82). By making one of its pistons very small, and the other relatively very large, a small total pressure of the first piston, or agent, becomes a large total on the large piston, or load, though the pressure per square inch is the same at both pistons. We may thus multiply the force upon the load to any desired extent, but the load will lose correspondingly in distance and speed just as in any other machine. But when we compute the work done by the small piston, and compare it with the work done upon the large piston, we find that the quantity of work, neglecting waste, is the same at both pistons (Fig. 185). F at large piston $\times$ distance it moves $= F$ on small piston $\times$ distance it moves.

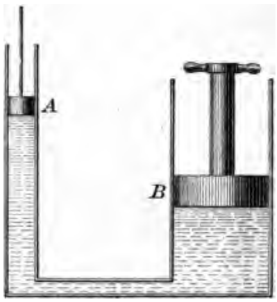


FIG. 183. — The work done by either piston is equal to the work done upon the other, wasted work being neglected.

Air may be used in the hydraulic press, but because gases are so easily compressed there will probably be a large amount of the energy wasted in compressing the air; hence the use of the *slightly* compressible liquids gives a higher efficiency.

QUESTIONS AND PROBLEMS

1. When a horse pulls a wagon up a hill, is the wagon lifted the length of the hill or its vertical height? Is the pull of the horse exerted throughout the entire length of the hill or its vertical height?

2. When one object moves another, what two things must be known to find the work done? When an object is lifted vertically, what two things must be known to find the work done?

3. To compute the work of a horse in drawing a load up a hill, what must be known? To compute the work done in lifting the wagon vertically, what must be known?

4. If the top of a uniformly steep hill is 20 ft. higher than its base and the length of the hill is 100 ft., find the work which must be done in lifting a wagon weighing 500 lb. up the entire height of the hill.

5. Neglecting the waste, how much work must a horse do in pulling the wagon to the top of the hill, problem 4? How many pounds must the horse pull?

6. A man finds that to load a barrel on a wagon by rolling it up a plank, one end of which rests upon the wagon, is "easier" than to lift it directly into the wagon. Does "easier" mean that it requires less force or less work to get it from the ground to the wagon? Why?

7. In the case of problem 4, oiling the axles of the wagon makes it "easier" for the horse to take the wagon up the hill. Explain what "easier" means in this case.

8. If a barrel weighs 250 lb. and a wagon is 5 ft. high, find (*a*) the force when it is lifted directly into the wagon, (*b*) the force when it is rolled up a plank 15 ft. long, and (*c*) the work done in each case.

9. The contact surfaces of the two pistons of an hydraulic press are rectangular. The dimensions of one are 4 cm. and 5 cm.; of the other, 12 cm. and 15 cm. Find the total pressure on each piston when the pressure intensity is 3 gm. per sq. cm. at the small piston. Compute the work done by an agent in moving the small piston 45 cm. How far will the large piston move during the same time? Find the work done upon a load at the large piston, neglecting the waste. Why is there more wasted work if air is used instead of water?

VIII. MOTION IN A CURVED LINE

93. **How Motion in a Curved Line is Produced.** — According to the first law of motion, a body in motion, when not acted upon at all, will move with a constant velocity in a straight line. From this it is plain that a body when not acted upon cannot move in a curve. Whenever curved motion is observed, we must conclude that something is continuously acting upon the body describing the curve. A curved motion may be produced by a single body acting continuously on one that already has a velocity For example, when a ball, attached to a string, is moving in a curved path, as shown in Figure 186, it is the string, indirectly the hand, that compels the ball to move in this curve by its continuous action, always at right angles to the motion of the ball. When the string is released or breaks, the ball no longer moves in this curve, but then moves, at first, in approximately the direction in which it was going at the instant the string ceased to act. It must be borne in mind that the earth is always attracting the ball, and this earth pull modifies the motion of the ball when the string ceases to act. On this account the ball goes vertically upward if released when in position (1), but with a *decreasing speed.* If released when in positions (2) and (4), though starting in the direction of the tangent, the ball will move in a new curve, the earth pull

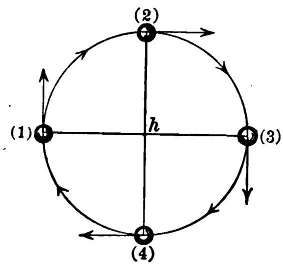


FIG. 186. — The ball, when released at any point, leaves the curve in the direction of the tangent at that point.

now producing the change in direction. When released in position (3), since the earth pull or weight is in the same direction as the motion at that instant, its only effect will be to *increase the speed* of the ball. These different weight effects as here shown are excellent examples of the application of the second law of motion. From these and many similar facts it is evident that a body while moving in a curve is continuously acted upon by some other body; similarly, when the parts of a body move in curved paths, these parts must be acted upon or attracted by other parts of the same body; for example, certain parts of a revolving wheel, by their cohesion, pull upon and compel the other parts to move in circular paths.

94. Centripetal Force; Centrifugal Force. — The force with which a body acts, when it compels another body to move in a curved instead of a straight line, is called *centripetal force.* In the case of the ball and string the tension or pull of the string is the centripetal force. In a flywheel the cohesion of the molecules of the wheel may be called the centripetal force.

As expressed in Newton's third law, action and reaction are always equal and oppositely directed. Hence the action of the string upon the ball (Fig. 186) has associated with it, as we say, an opposite and equal pull or reaction of the ball upon the string. This *reaction* is called *centrifugal force.* Since this *reaction* of the ball ceases as soon as the string ceases acting, the centrifugal and centripetal forces disappear at the same instant; that is, at the instant when the body begins the tangential motion. The common notion that centrifugal force causes a body to fly from a center, as the origin of the word suggests, is plainly erroneous. However, it is often convenient to refer to centrifugal force as though it had an independent existence.

The amount of the centripetal or centrifugal force, in any case, will evidently be greater when the mass of the body which is being moved away from the straight line is greater. Also, if the body which is receiving the curved motion has its velocity

increased, it follows that there must be a more rapid changing of the direction; hence the centripetal force required to produce this change must be greater.

Every one who has ever tried to run or skate with constant speed in circles of different radii knows that his feet push harder outward against the ground or ice when the radii of the circles become smaller. In order that a body may move in a curved path, there must be a continuous reaction between the body and something else. For this reason the outside of the circus track and the outside rail of a railroad curve are elevated, when the horses and trains are required to move rapidly around curves of short radius. The actions of the ground, the ice, and the railroad rail in the cases mentioned constitute the centripetal forces. These facts show that the centripetal and centrifugal forces become greater as the radius of the curve becomes less.

The relations are expressed by the following formula:

$$\begin{array}{c}\text{centripetal force}\\ \text{or}\\ \text{centrifugal force}\end{array} = \frac{\text{mass} \times \text{veloc.}^2}{\text{radius}}$$

Straight line motion is the simplest, but in actual life is rarely met with. It is only by neglecting the motion of the earth and calling a small portion of the earth's circumference a straight line that we obtain most of our so-called examples of motion in a straight line.

Application of the Principles of Centrifugal Motion. — When solids are wet, the liquid may be separated from the solid by putting them into a perforated cylinder and increasing its speed of rotation until the adhesion of the liquid for the solid is no longer able to pull the liquid into the circle; whereupon it separates from the solid. In this manner clothes are partly dried, instead of being run through a wringer, and oil is similarly recovered from iron scraps, holes being provided for the escape of the liquid around the outside of the cylinder. Liquids of different density, when rotated in a vessel, will arrange themselves in the order of their densities, the densest being

on the outside or circle of larger radius. In this manner the oily part of milk, the cream, may be separated from the more dense portions called skimmed milk.

Machines of a similar kind, usually called *centrifugal* machines, are used in making pottery, refining sugar, and for a variety of other purposes.

Questions

1. Explain the occasional bursting of rapidly rotating grindstones and flywheels.

2. Explain the "skidding" of automobiles and bicycles when turning sharp curves at a high speed. Why is the danger greater on wet streets?

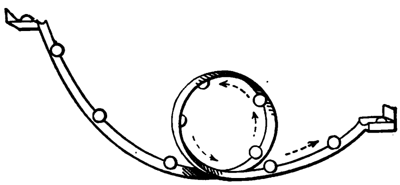


Fig. 187. — A "loop the loop."

3. What effect does the rotation of the earth have upon the weight of a body? Where is the effect the greatest? where the least?

4. If you swing a pail of water rapidly in a vertical circle, the water will not fall out when the pail is inverted over your head. Explain.

5. Explain why the ball follows the curve in Figure 187.

6. Why does a very heavy flywheel keep machinery running more uniformly, particularly when the work done by the machine is variable?

IX. THE PENDULUM

95. A Study of a Simple Pendulum. — A lead ball, say 1 cm. in diameter, attached to one end of the finest wire that will support its weight, the other end of the wire being fastened to a support as shown in Figure 188, constitutes the simplest practical pendulum. When the ball is at rest the wire is vertical, and the arrangement may be called a *plumb line*.

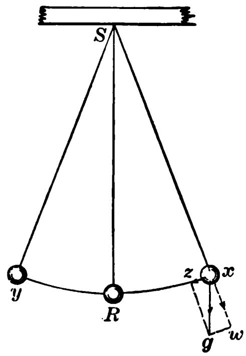


FIG. 188.

If the ball is displaced from this point of rest to another point x, it will then be in a higher position than when at R; hence when released it will fall from x on account of its weight or gravity. Since it is acted upon by the wire as well as the earth, the ball cannot fall vertically, but must move in a curved path toward R. This curve is the arc of a circle, the center of which is called the *center of suspension*. The weight of the ball xg can be resolved at any point x into two components; the one, xw, is counterbalanced by the string, the other, xz, is the component that moves the ball. The value of xz is smaller the nearer the point x is to the point of rest R. When the ball arrives at R, it has a considerable velocity, hence kinetic energy, acquired by its fall, and consequently does not stop there, but continues to move until the earth pull, as the ball rises, removes all the motion, the energy being transformed into the potential form. Since this is just the reverse of adding the velocity, it would take just as long for the earth pull to remove the velocity

as it did to give it, and the ball would rise to a point y the same distance from R that x is, provided, of course, that nothing else hindered its motion. But because the *air must be moved* and the *wire bent* at the top, these hindrances will, each time it swings, diminish the distance that the ball rises until it finally ceases to move. If all the hindrances and consequent waste of energy could be completely withdrawn, the pendulum would vibrate indefinitely. This motion of the pendulum furnishes one of the simplest cases of a *vibration* or an *oscillation*. The motion from x to y is called a single vibration; from x to y and back again is called a complete or double vibration. For the pendulum the time required to perform a single vibration is called the *period* or time of vibration.

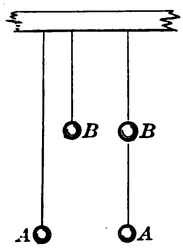


FIG. 189. — A and B when fastened together constitute a compound pendulum.

The distance from the center of suspension to the *center of oscillation*, a point approximately at the *center of the small ball*, is called the *length* of the pendulum. The arc measured from the point of rest to an extreme position of the ball, the arc Rx (Fig. 189), is called the *amplitude*. If the body vibrating as a pendulum is not very small, the center of oscillation and the length of the pendulum are not easily found. Such a pendulum, equivalent to a number of simple pendulums fastened together, is called a compound pendulum (Fig. 189).

Laws of the Pendulum. — Experiments prove (Fig. 189): (1) the time of a vibration or *period* of a pendulum is independent of the amplitude up to about 3° or 4°; (2) the period varies directly as the square root of the length; (3) the period is independent of the weight or kind of material used as a bob, provided the air resistance is eliminated; (4) the period varies inversely as the square root of the acceleration of gravity.

These laws can be briefly expressed thus: *For small amplitudes the period* (t) *varies directly as the square root of the*

length (l) *and inversely as the square root of the acceleration of gravity* (g); *that is, t varies as* $\sqrt{\frac{l}{g}}$.

Since at a given place g is constant, the period of a pendulum may be kept constant by keeping both its amplitude and its length constant. For this reason, the pendulum is used to regulate the motion of clocks, in which an arrangement called an escapement is so arranged that each complete vibration allows the wheelwork to move forward one cog. The energy required to keep the clock going, that is, to supply the loss occasioned by the air and friction, is furnished from the potential energy of a raised weight or a coiled spring. Because a change in the length of the pendulum changes the period, the clock may be set to run faster or slower by shortening or lengthening the pendulum rod. Heating and cooling produce an expansion and contraction which may thus change the pendulum length and affect the accuracy of the clock as a timekeeper. This change in length may be compensated for by methods that will be noted in section 115. Because the weight for a given body increases as it is taken from the equator toward the poles, it follows that the same pendulum will make one vibration in less time if it is carried away from the equator. The length of a pendulum which vibrates once per second, known as the *seconds pendulum*, must vary with the latitude; in New York its length is 39.1 in. or 99.3 cm. From the formula connecting t, l, and g it can be seen that the value of g may be found by the use of a pendulum.

Questions and Problems

1. What causes a pendulum to vibrate? Would a given pendulum make one vibration in less time when near the equator or near the poles? Why?

2. What is the purpose of the mainspring in a clock? What is the purpose of the pendulum? If a clock runs too fast, what change would correct it?

3. Find the length of a pendulum which vibrates three times in 2 sec.

4. If the times of vibrations of two pendulums are to each other as 3 to 4, and the length of the first is 25 cm., find the length of the second.

5. Find the value of g where a pendulum 100 cm. long vibrates once in each second.

6. A pendulum 36 in. long makes a vibration in ¼ the time that another requires. How long is the second pendulum?

7. What effect would an increase in the earth's attraction have on the time of a pendulum? What use of the pendulum does this suggest?

X. HEAT

Heat a Form of Energy

96. First Ideas of Heat obtained from Sensations. — By means of certain nerves, distributed over the surface of the body, we are able to determine the existence of something familiarly called *heat*. Through the use of our hands chiefly we have learned to decide in a general way whether a body is hot or cold, and whether it is gaining heat or losing it. Though much valuable knowledge is accumulated in this manner, it frequently happens that our conclusions, based on the information conveyed through this *temperature sense*, are very inexact, if not wholly wrong. For example, if one hand is put into ice-cold water, and the other into as hot water as it can endure, and after a minute or two both hands are thrust quickly into water at about the normal temperature of the blood, 98° F., this same water will feel cold to the one hand but warm to the other. In this case, the conclusions based on sensation are plainly contradictory.

97. Mechanical Energy can generate Heat. — When we rub our hands together vigorously, the nerves in them tell us that we are generating or producing heat, for both hands grow warm faster when rubbed than when held quietly in contact. The more we press them together as we rub, the more mechanical work we must do in rubbing them, and at the same time the more heat is generated. Again, if we rub a cent on the table, bend a wire back and forth quickly until it breaks, or pound a piece of lead with a hammer, in all these and in many similar cases we are conscious of doing mechanical work, and our hands, with their nerve thermometers, will tell us that we are also producing heat. When a gas is being compressed, heat is gen-

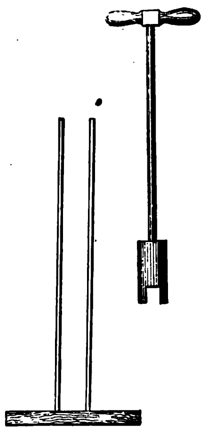


FIG. 190. — If a piece of tinder is placed in the cavity of the piston and the piston thrust quickly into the cylinder, the heat generated sets fire to the tinder.

erated, as is shown in using the bicycle pump or in the experiment of setting fire to an inflammable substance by compressing air with the so-called fire syringe (Fig. 190).

In general, it is found that whenever any visible or mechanical motion is either decreased or destroyed, without producing a corresponding visible motion of something else, a quantity of heat is generated. We know from our previous study that a moving body has energy, and we observe that, as the energy of moving bodies disappears, heat generally appears in its place. This constitutes our *first reason* for concluding that *heat* is another *form of energy* into which the energy of mechanical motion has been changed.

98. **Heat can produce Mechanical Motion.** — Let a flask *A* containing air be placed in communication with a bottle of water by means of a glass tube passing through one of two holes in the stopper of the bottle *B*, and let a second tube *C* extend from the bottom of the bottle to a distance of a foot or two above the top of the bottle (Fig. 191). When the air in the flask is heated, the water in the bottle is driven up the tall tube *C*. Since the lifting of a body is the doing of work, the heated air is doing work. The amount of the work could be roughly computed by weighing the water in vessel *D*

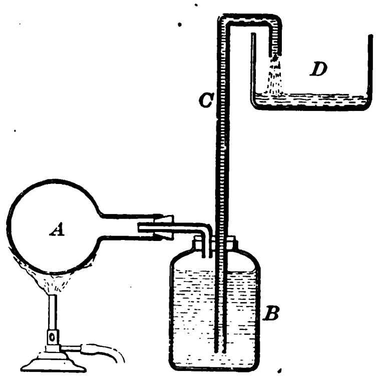


FIG. 191. — Heat going into the air *A* increases its ability to do work; heat is a form of energy.

and measuring the distance through which it has been lifted. By heating the air we have given it *the ability to do work.* But we have defined *the ability of a body to do work as its energy,* hence the *heat* given to the air must have been a *form or kind of energy.* In the fact that heat can produce mechanical motion or do work, we find our *second reason* for believing that heat is one of the many forms or varieties of energy. In general, since well-known forms of energy can be converted into heat, and since heat in turn can be converted into well-known forms of energy, the conclusion has been reached that heat itself must be one form or manifestation of energy.

A single experiment which shows both these transformations can be performed as follows: Take a rubber band about ¼ in. wide and 1 or 2 in. long, place it in contact with the lips, letting it remain until it acquires their temperature. Now suddenly stretch the rubber nearly to breaking; note the rise in temperature. The hands do work on the rubber and generate heat. After the rubber again acquires the temperature of the lips, let it slowly pull your hands together. Note the fall in temperature. The rubber in this case does work upon the hands, and some of its heat is converted into mechanical motion.

99. Some Effects produced by giving Heat Energy to or withdrawing it from a Body. — When a body is being heated or cooled, that is, when the amount of its heat energy is increased or decreased, the body may undergo one or more important changes commonly known as the effects of heat. The most important of these effects are here enumerated because a brief knowledge of some of them must be assumed in studying the others.

(1) The body may get warmer or colder; its temperature may change. (2) The body may expand or contract; its dimensions may change. (3) The body may change its state, solid to a liquid, liquid to a gas, or the reverse. (4) The body may change its pressure upon outside bodies, as a gas changes its pressure upon the walls of the containing vessel. (5) The body may experience a change in any of the so-called special properties, such as hardness, ductility, conductivity, etc.

These effects will be more fully considered under separate topics.

100. Conclusion as to the Nature of the Form of Energy called Heat. — On account of the relation of heat to the various effects enumerated in the last paragraph, we are led to believe that the heat of a body is due to, or rather consists in, the vibratory motion of its molecules, hence that heat is a variety of kinetic energy. According to this view, a body that is being warmed is having the vibratory motion of its molecules increased, and a cooling body is having its molecular motion diminished. As a body grows warmer, this increased molecular motion will require an increased space between the molecules, and the body grows larger in volume; that is, it *expands*. Again, if the substance heated is a gas, which is not allowed to expand, the increased molecular motion will result in an increased molecular bombardment of the walls of the vessel or increase the *pressure* of the gas. A change in the distances between the molecules produces in turn other changes, such as those mentioned under the head of *changes in state*, and *changes in special properties*. This view of the nature of heat already mentioned under the topic, Kinetic Theory of Matter (section 21), will be more easily appreciated as we develop in accordance with this doctrine our understanding of the various effects of heat. In brief, we believe that the molecular motion or the agitation of the particles of a body increases as the body gets warmer, decreases as it gets colder, and ceases only when a body is deprived of all its heat, a condition not found in nature and not yet attained in experiment.

The word *cold* is often used as though it indicated something of a nature the opposite to that of heat. This use of the term *cold* is very confusing, and often interferes with the forming of correct views concerning heat. Cold as an adjective indicates a heat condition of a body relative to our own bodies, in contrast to that expressed by the adjective hot. In this sense cold is a useful term. To define *cold* as the absence of heat makes the confusion even worse, since none but bodies

entirely deprived of heat would then be entitled to the term, and no such heatless body has ever been obtained. Cooling, which means the removal of heat, should not be spoken of as the giving of cold. To say that cold has been given to a body which had had a part of its heat removed, is just as misleading as to say that a vacuum has been given to a vessel which has a part of its air removed. For this reason, the word *cold* as a noun or substantive should not be used in studying heat.

101. **Sources of the Earth's Heat Energy.** — If we believe that heat is a form of energy, all heat must be obtained either from some body in which heat already exists, or it must be obtained from some other form of energy. We shall now consider some of the most important of these sources of heat.

(1) *The sun*, by a process known as radiation (see page 222), is constantly sending forth in all directions, in the form of waves, an enormous quantity of energy. A small portion of these waves of radiant energy reaches the earth as light and heat. Though most of the heat thus obtained is quickly radiated off by the earth, much of it is utilized in producing the various changes which go on in nature, such changes, for example, as the expansion of air, the evaporation of water, and the growth of plants.

(2) As already shown, heat may be produced from *mechanical energy* by different processes, known by such terms as *friction, impact,* and *compression.* Examples of these are found in such familiar facts as the heating which occurs at the axles of cars, the flash of fire when a horse's shoe strikes a stone, and the heating of the air as it is compressed in a bicycle pump. The source of the heat in all these cases is the same, mechanical energy, though the process of producing the change has different names.

(3) The burning of wood, coal, gas, and other substances, the slaking of lime by adding water, the dissolving of metals in acids, are all examples of what is known as *chemical action,* and they are all accompanied by a generation of heat. The source of the heat in these cases is said to be the potential energy of

chemical separation; but, like all so-called potential energy, it has never been satisfactorily explained.

(4) An electric lamp or the electric heater in a trolley car shows that *electric energy* may also be used as a source of heat; but most electrical energy is itself directly traceable either to chemical action (The Voltaic Cell, sec. 252), or to mechanical motion (Dynamo-electric Machines, sec. 300). Other forms of energy, such as *sound* and *light*, may also be converted into heat; but the actual quantity of energy in these forms is generally so small that they have no practical value as a source of heat. We see, then, that the chief *available sources* of heat are the *sun*, *mechanical energy*, and *chemical energy*. But since the potential energy of the common fuels, such as wood, coal, and petroleum, may be traced back to the radiant energy of the sunshine which produced the growth of the plants from which these fuels came, and also because the energy of the wind and water, which constitute the chief source of mechanical motion where no fuel is used, is likewise due chiefly to the radiant heat of the sun, it follows that sunshine is not only the most important, but, directly or indirectly, the only important source of the available energy of the earth.

102. The Effect of Heat called Warming and Cooling or Changing Temperature. — Probably the earliest observed, and certainly one of the most important, of the many effects which may occur when heat is given to a body, is that commonly called warming or raising the temperature. As suggested we believe that this warming is accompanied by an increased molecular motion. If 1 lb. of water is placed over a given flame, it will experience about twice the change in temperature in one minute that 2 lb. would undergo in one minute when receiving as much heat from another flame exactly like the first. Since both quantities of water receive about the same quantity of heat energy, it follows that the amount of change in temperature does not depend alone upon the amount of heat given. For in both

cases as the water gets warmer the average energy of the molecules increases, but when the 2 lb. are heated, since the same quantity of energy is given to twice the number of molecules, there is only about half the gain for each molecule.

If two bodies have been in contact with each other for some time, until neither gives heat to the other, they are said to have the same temperature. But when two bodies are in contact, and one of them gives up heat to the other, the one which is losing heat is said to have the higher temperature. It follows that the term *temperature* expresses one of the conditions of a body on which depends its ability to give heat to or receive heat from other bodies.

103. **How Changes in Temperature are detected and measured; the Principle of the Thermometer.** — Ordinarily we find approximate answers to the questions "how warm" or "how cold" a body is by means of our sensations, or our temperature sense. This method of determining temperature, though direct and convenient, is inaccurate, and in many cases impracticable. Since this direct method is unsatisfactory, we must determine temperature changes indirectly, that is by observing some of the other effects of heat which accompany the change in temperature. A study of the different effects of heat mentioned in section 99 has shown that expansion and change of pressure are best suited to indicate a change in temperature. Though neither a change in the volume of a liquid nor a change in the pressure of a gas is really a change in temperature, yet because both of these effects accompany a change in temperature, in a fairly uniform manner, they serve to detect and measure temperature changes. Upon these principles are constructed instruments called *thermometers* which serve to *determine temperature and changes in temperature.*

104. **The Measurement of Temperature by Expansion; filling the Mercury Thermometer.** — Mercury expands at a practically uniform rate, and is well suited for the construction of

thermometers. A glass tube with a bulb at one end is first filled with mercury. The tube and mercury are then heated to the highest temperature which it is proposed to measure with the thermometer under construction. The air having all been thus displaced by the expanding mercury, the tube is then sealed by melting the glass at the top. As the mercury cools it contracts, leaving nothing but a very little mercury vapor in the upper part of the tube — almost a vacuum. Since mercury expands and contracts at a greater rate than does glass, we now have an instrument which, by the rise and fall of the mercury, will readily show *changes* in temperature, but nothing more; it is only a *thermoscope.*

105. The First Step in the Graduation of a Thermometer; finding the Fixed Points. — To determine the actual amount of change in temperature in any case, and to make it possible to compare the records of one thermometer with those of another, we must have (1) one or more easily determined temperatures called the *fixed points,* and (2) a method of dividing the distance on the tube in relation to the fixed points. Careful experimenting has shown (1) that the temperature at which pure ice melts is practically constant, and (2) that the temperature of steam as it comes from boiling water is likewise constant when the pressure upon the water is constant. Upon these two facts, first suggested for this purpose by Newton in 1701, depends the location of the fixed points on the scales of thermometers. After filling and sealing as already stated, the bulb, including as much of the stem as practicable, is placed in a vessel of finely broken ice (Fig. 192). When no further change takes place, the final position of the top of the mercury column is then

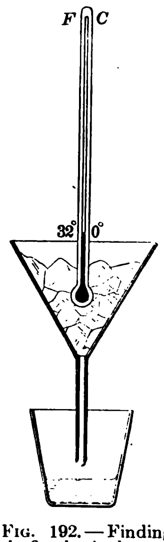


FIG. 192. — Finding the fixed point known as the freezing point.

marked. This is the freezing point of water or the melting point of ice, the first of the fixed points. The thermometer is then put into a steam generator similar to that shown in Figure 193 and left until the mercury ceases to expand. If the pressure of the atomsphere is 76 cm., standard atmospheric pressure, the top of the mercury column is then marked. This boiling point of water is the second of the fixed points of a thermometer. (For the effect of pressure on the boiling point, see section 129.)

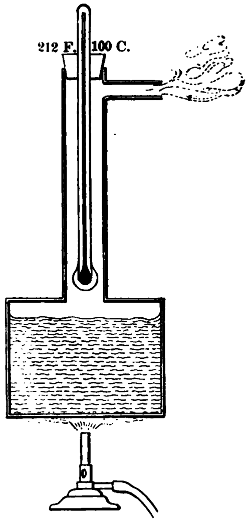


FIG. 193. — Finding the fixed point known as the boiling point of water.

106. The Final Step in the Graduation of Thermometers. — The difference between the temperatures of melting ice and boiling water, or the two fixed points on thermometers, has been variously subdivided into temperature units called degrees. Celsius of Sweden, in 1742, called the freezing point zero, marked 0°, and the boiling point 100° (Fig. 194). Since there are 100° or temperature units between the two fixed points, a thermometer graduated according to this system is usually called a centigrade thermometer. This form is used almost exclusively for scientific purposes. In another system of graduation, due to Fahrenheit of Germany, the freezing point of water is marked 32° and the boiling point 212° (Fig. 194). On this scale the difference between the two fixed temperatures is divided into 180°. The Fahrenheit thermometer is used by our weather bureau, physicians, and by English speaking people gen-

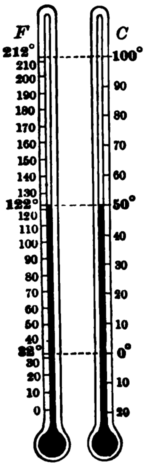


FIG. 194. — A comparison of the Fahrenheit with the centigrade thermometer.

erally, for all except scientific work. Since the difference which exists between the temperature of the freezing and that of the boiling point is divided into 100° on the centigrade scale and into 180° on the Fahrenheit scale, it follows that 1 degree on a centigrade thermometer has a larger value than 1 degree on a Fahrenheit thermometer. The same change in temperature that is indicated by 1° C. is indicated by $\frac{180}{100}$ or $1\frac{4}{5}$° F. Similarly 1° F. is equivalent to $\frac{100}{180}$ or $\frac{5}{9}$ of 1° C.

107. How to change a Scale Reading in One System to a Scale Reading in the Other.—In changing the reading on the scale of one thermometer to a reading in the other system we must take into account not only the different values of a degree as just given, but also the fact that the zero or starting point is differently located on the two scales. The zero or starting point of the scale on a Fahrenheit thermometer, through the inventor's mistaken belief that nothing could be colder, was located 32° below the freezing point, whereas the centigrade more logically begins the count at the freezing point as shown in Figure 194.

Temperatures below either zero are usually written with the minus sign preceding them. For example, −15° C. means a temperature which is 15 centigrade degrees below zero and also 15° below the freezing point.

Similarly, −15° F. means 15 Fahrenheit degrees below zero, but since the zero is itself 32° below the freezing point, it follows that a scale reading of −15° F. is 32° + 15° or 47° F. below the freezing point.

On account of the location of the zero, a Fahrenheit *scale reading* must first be changed to a *freezing point reading* by subtracting or adding 32 degrees before it can be changed into a centigrade reading. Similarly, when a centigrade reading is being changed to a Fahrenheit reading, after the equivalent number of Fahrenheit degrees has been found, 32 degrees must be added or subtracted in order to convert the freezing point

reading to a scale reading. For example, a temperature of 68° F. means 68° − 32° or 36° above freezing point, and the equivalent number of centigrade degrees is $\frac{5}{9}$ of 36° or 20°. But 20° C. above freezing is also 20° on the scale, hence a temperature of 68° F. is the same as a temperature of 20° C.

FIG. 195.— When taking a temperature, the thermometer should, if possible, be surrounded by the substance.

Briefly: $\frac{5}{9}$ of (F. reading − 32°) = C. reading

$\frac{9}{5}$ of C. reading + 32° = F. reading.

Proper attention must be given to the signs.

108. The Two Uses and the Range of a Thermometer. — It must be carefully noted that a thermometer may be used (1) to determine the temperature of a body at any time, and (2) to measure the change that takes place in the temperature of a body, both results being expressed by a number of degrees. A single reading of a thermometer when in contact with a body gives what is called its temperature, but the difference between two readings taken at different times determines the body's change of temperature (Fig. 195).

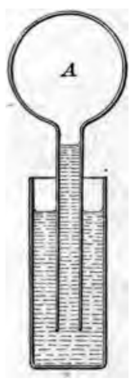


FIG. 196. — Showing Galileo's form of thermometer. The liquid rises and falls in the stem with a change of the temperature of the air in the bulb *A*.

The freezing and boiling points of the liquid used in the tube of a thermometer determine the lowest and highest temperature which that particular kind can possibly indicate. By consulting tables of freezing and boiling points it can readily be seen that the greatest possible range of an alcohol thermometer is from − 130° to 78° C., while that of a mercury thermometer is from − 39° C. to 357° C.

109. The Standard Gas Thermometer. — The thermometer was invented by Galileo in 1597. He used a glass bulb filled with air, with the open end of the tube placed in colored water, as shown in Figure 196. Air and

other gases are particularly well suited for the measurement of temperature (1) because they expand a great deal for a slight change in temperature and (2) because they expand uniformly. Though Galileo's form of gas thermometer was very sensitive, its indications were not reliable because any change in the atmospheric pressure also produces changes in the volume of the confined air. A better form of gas thermometer is that shown in Figure 197. The air is confined in the bulb A by means of a column of mercury, in the rubber tubing. The level of the mercury can be changed at will by raising or lowering the open glass tube O. In this form of thermometer we use the principle that a gas, which is not permitted to expand, increases its pressure against the containing vessel as its temperature rises and decreases its pressure as the temperature falls. Hence any method by which we can measure the pressures of the gas at different times will provide a method of determining temperature. By adjusting the level of the open tube the air in A is kept at a constant volume. The gas in the bulb A is then always under either the atmospheric pressure at O, or as much more or less than the atmospheric pressure as is shown by the difference between the levels of the two mercury columns. By reading the barometer and finding the difference between the two levels the pressure of the gas at any time can be found and the temperature computed. Because of its low liquefying point, hydrogen is well suited for a gas thermometer. On account of its sensitiveness and its accuracy, a well-constructed hydrogen thermometer is valuable in the hands of an experienced investigator, but it is too difficult of manipulation to use for ordinary work.

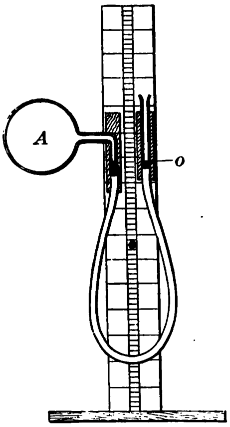


FIG. 197.—A gas thermometer. The rubber tube connecting the glass tube O with the bulb A is completely filled with mercury.

Questions and Problems

1. A body changes its temperature 4° C. The same change of temperature would be indicated by how many degrees F.?

2. If a body has a temperature of 4° C., is it above or below zero? Is it warmer or colder than freezing water?

3. If a body has a temperature of 4° F., is it above or below zero? Is it warmer or colder than freezing water?

4. What are the fixed points on a thermometer and how are they found? Do the centigrade and Fahrenheit systems use the same fixed points? Are they marked the same?

5. A comfortable temperature for the air in a living room is 68° F.; how many degrees is this above the freezing point? What would be the reading of a centigrade thermometer hanging in the same room?

6. The melting point of phosphorus is 45° C. How many degrees is this above the freezing point of water? Find the equivalent number of degrees F. (recall the reading of the freezing point) and find the melting point of phosphorus on a Fahrenheit thermometer.

7. Change a reading of 4° C. to Fahrenheit; 10° C. to Fahrenheit; − 40° C. to Fahrenheit; 98° F. to centigrade; 10° F. to centigrade; −10° F. to centigrade.

8. Supposing that the absolute zero (sec. 120) is 273° below zero on the centigrade thermometer, commonly written − 273° C., find the reading of the absolute zero on the Fahrenheit scale.

9. The boiling point of liquid air at ordinary pressure is −182° C. Find its boiling point as shown by a Fahrenheit thermometer.

10. If you wish to have the degree marks on a thermometer far apart, must the bulb be large or small? the bore of the stem large or small? State the advantages and disadvantages of a large bulb; of a small bore.

The Measurement of Heat; Calorimetry

110. Quantity of Heat; Heat Units. — Recalling our fundamental idea that heat is a form of molecular energy, it follows that the quantity of heat which is required to warm the water in a vessel will depend upon two things: (1) the quantity or mass of water to be warmed, and (2) the number and kind of degrees through which its temperature is to be raised. We believe that it always requires the same quantity of heat to warm 1 lb. of water from 32° to 33° F. This quantity of heat,

called the British Thermal Unit (B.T.U.), is commonly used by British and American Engineers as a unit to measure other quantities of heat. To warm 1 lb. of water through any other 1° F., say from 41° to 42° F., requires approximately the same quantity of heat.

The scientific world in general uses as a heat unit *the quantity of heat required to warm 1 gm. of water through 1° C.* This heat unit is called the *gram calorie or small calorie.* From the definition of the gram calorie, it follows that to warm 10 gm. of water through 1° C., it is necessary to supply 10 gm. calories, that is 10 times as much heat as is required to warm 1 gm. of water through 1° C., and to warm 10 gm. of water through 18° C. the water must receive 18 times as much heat as is required to warm the same mass through 1° C., hence there will be required $18 \times 10 = 180$ gm. calories. It is evident that the number of grams of water heated multiplied by the number of degrees C. through which the temperature is raised gives the number of gram calories required to warm it.

$$\text{no. gm.} \times \text{no. degrees C.} = \text{no. calories.}$$

In a similar way, when water is cooling we may find the number of gram calories given off by knowing (1) the number of grams of water, and (2) the number of degrees C. through which it cools. For example, 16 gm. of water cooling from 64° C. to 28°, that is, cooling through 36°, will give off $36 \times 16 = 576$ gm. calories. The heat required to warm 1 k. of water through 1° C. is sometimes used as a heat unit. This heat unit, called the *large calorie,* is obviously 1000 times as large as the gram calorie.

111. **Heat Capacity; Specific Heat.** — If equal masses of water, iron, and lead are so placed that each will receive as many heat units per minute as the others, at the end of a given time a thermometer will show that the lead has been warmed through about 30 times, and the iron about 9 times as many

degrees as the water. This shows that a given mass of lead requires about $\frac{1}{30}$ and an equal mass of iron $\frac{1}{9}$ as much heat to warm it one degree as an equal mass of water requires. These facts are sometimes expressed by saying that all substances do not have the same heat capacity.

If we compare the heat capacity of each substance with the heat capacity of water, we get a set of ratios known as specific heats. *The specific heat of a substance is the ratio of the quantity of heat required to warm any mass of the substance through 1° to the quantity of heat required to warm an equal mass of water through 1°.* Being a ratio, specific heat is a mere number without denomination.

The preceding definition of specific heat, being general, holds with all systems of units. But *when the gram calorie is taken as the unit of heat, the specific heat of a substance may be defined as the number of gram calories required to warm 1 gm. of it through 1° C.*

The following table gives the average specific heat of the most common substances, water being the standard. It is applicable to any units of mass and any thermometer:

THE SPECIFIC HEAT OF SOME COMMON SUBSTANCES

Air (at constant pressure)	0.237	Iron	0.113
Alcohol	0.453	Lead	0.031
Brass and copper	0.091	Mercury	0.033
Glass (crown)	0.161	Silver	0.056
Hydrogen (constant pressure)	3.406	Water	1.000

With the exception of the gas hydrogen, water has the largest heat capacity, that is, the largest specific heat of all substances. On this account water is well suited for conveying heat in the warming of buildings. For a similar reason the presence of a large quantity of water prevents a rapid change in the temperature of the air in contact with it, hence, large bodies of water moderate the climate in their vicinity.

To calculate the quantity of heat involved in the warming or cooling of any body, we must know (1) the specific heat of the body, (2) its mass, and (3) the number of degrees through which its temperature changes. For example, to warm 50 gm. of iron from 15° to 45° C. will require .113 (cal. pr. gm.) × 50 (mass) × 30 (degrees change) = 163.5 gram calories.

112. **The Principle of Exchange of Heat; The Method of Mixture used in finding Specific Heat.** — We have already called attention to the fact that when two bodies at different temperatures are brought in contact, the body which has the higher temperature will lose heat and the one with the lower temperature will gain heat until the temperatures are equalized, though time is always required for the change. Consequently, if we mix two liquids, or if we completely surround a solid by a liquid, we may conclude that the quantity of heat lost by the one body is equal to that gained by the other, though, on account of differences in specific heat, the changes in temperature are generally different. Thus, if a piece of silver at 90° C. weighing 200 gm. is put into 100 gm. of water at 10° C., we may assume that the quantity of heat lost by the silver is equal to the quantity gained by the water, and that they finally come to the same temperature, in this case 18.2° C.

To compute these quantities of heat we must know (1) the specific heat of each body, (2) the mass of each, and (3) the change in temperature which each sustains. That is, the number of gram calories lost by silver = number of gram calories gained by water.

$$\text{(for the silver) } .057 \times 200 \times 71.8$$
$$= \text{(for the water) } 1 \times 100 \times 8.2.$$

In general, whenever any two substances are so placed that the one must gain the heat which the other loses, it follows:

$$\overbrace{\text{sp. ht.} \times \text{mass} \times \text{temp. change.}}^{\text{First Substance}}$$
$$= \overbrace{\text{sp. ht.} \times \text{mass} \times \text{temp. change.}}^{\text{Second Substance}}$$

Any one of the six factors in this equation may be computed provided the other five are given or have been found experimentally. If water is one of the two substances, there are only five variable factors, for the specific heat of water, the standard, is always taken as 1.

By finding the mass of a given substance, its change in temperature, and the change in temperature which a known mass of water undergoes when the body is placed in it, we may find the specific heat of the body. This relation is expressed briefly in the following equation: —

$$\underset{\text{Substance}}{\text{sp. heat} \times \text{gm.} \times (t_1 - t_2)} = \underset{\text{Water}}{1 \times \text{gm.} \times (t_2 - t_1)}.$$

t_1 means first temperature of each substance, and t_2 the second temperature, common to both.

When more than two bodies are involved in the heating and cooling, they must be included in the computation, for, as before, the sum of all the quantities of heat lost is equal to the sum of all the quantities of heat gained.

Questions and Problems

1. How much heat is required to warm 10 gm. of water 1° C.? How much to warm 10 gm. 25°? How much to warm 65 gm. of water from 11° to 17° C.? How much heat is given out by 30 gm. of water cooling from 95° to 15°?

2. When two liquids having different temperatures are mixed, what is the relation between the quantity of heat lost by the warmer and the quantity of heat gained by the colder, neglecting any loss of heat through the vessel?

3. If the liquids mixed are water, how is the temperature of the mixture related to the two original temperatures (*a*) when the masses are equal? (*b*) when the colder mass is to the warmer as 1 : 2? (*c*) when the colder is to the warmer as 3 : 4?

4. If the liquids mixed have equal masses but are different substances, explain why the temperature of the mixture will not be halfway between the original temperatures of the two bodies.

5. What three things must be known to find the heat required to warm, or the heat given out by the cooling of any body?

6. If 30 gm. of water at a temperature of 56° C. are mixed with an equal mass of water at 0° C., find the resulting temperature.

7. Find the temperature of the mixture when 64 gm. of water at 23° C. are mixed with an equal mass at 87°.

8. Find the temperature of the mixture when 60 gm. of water at 14° are mixed with 80 gm. of water at 58°.

9. Give the meaning of the statement that "the specific heat of iron is 11."

10. Does the kind of thermometer used in finding the specific heat of a body affect the value found? Why?

11. The heat given out by 25 gm. of water cooling 1° is sufficient to warm 1 gm. of iron through how many degrees? The same quantity of heat would warm 10 gm. of iron through how many degrees?

12. A piece of iron weighing 320 gm. and having a temperature of 80° C. is dropped into an equal mass of water at a temperature of 15° C. Find the resulting temperature of the iron and water, the heat required to warm the vessel being neglected.

13. Find the final temperature when 450 gm. of copper at 75° C. are mixed with 200 gm. of water at 15° C., contained in a glass vessel weighing 40 gm.

14. If 120 gm. of water at 16° C. and 720 gm. of metal at 100° C. when mixed give a final temperature of 30° C., find the specific heat of the metal.

15. The heat required to warm 1 gm. of copper 1° would warm 1 gm. of water what part of 1°? The same quantity of heat would warm what part of 1 gm. of water 1°?

16. Find the amount of water, called the "water equivalent," which would require as much heat to warm it 1° as is required to warm 100 gm. of brass 1° C.

17. Find the water equivalent of 200 gm. of lead.

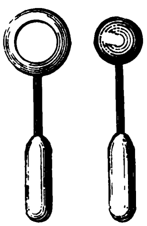


FIG. 198. — The ball barely goes through the ring when both are at the same temperature.

THE CHANGE IN DIMENSIONS ACCOMPANYING A CHANGE IN TEMPERATURE

113. The Expansion and Contraction of Solids. — A metal ball that will just pass through a ring of the same metal, if both are at the same temperature, will become too large for the ring when the ball is heated and the ring is not (Fig. 198). The increase in the volume of the ball, without any addition of material, is called cubical expan-

sion or dilatation. Most solids undergo a similar expansion with a rise of temperature. The expansion of solids is always small in comparison with the size of the body, and in many cases great care must be taken in order to detect it. Though expansion always involves an increase in volume, when studying solids we may confine our attention to their increase in length alone, this being known as *linear expansion*. The linear expansion of a metal bar, such as a poker or gas pipe, can easily be shown by placing one end of the bar against a rigid support and letting the other rest on a large needle or wire which has a pointer attached (Fig. 199). As the bar is heated the expansion will produce a motion of its free end, and the rolling of the needle on which the movable end rests will move the pointer, thus making visible to the eye a motion which would probably escape direct observation.

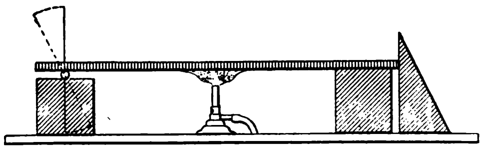


FIG. 199. — The heat from the flame expands the box, thus rolling the rod with the attached pointer at the left.

114. The Coefficient of Linear Expansion. — Do all solids have the same rate of expansion? An answer to this question can be given in the following way:

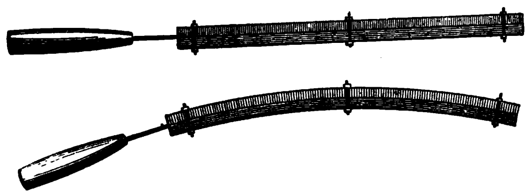


FIG. 200. — The brass, at the top, has a larger coefficient of expansion than the iron.

Let a straight bar of brass be riveted at several points to a bar of iron of the same length, as shown in Figure 200. If this compound bar is heated, the two metals, lying side by side, experience the same change in temperature, but the curving of the bars shows that the brass, which is on the outside of the curve, has expanded

more than the iron. Since they were originally of the same length, the brass has increased a larger portion of its length for the given change in temperature.

How can we determine the rate of linear expansion of a solid? If we measure the length of any solid, take its temperature, then heat it, take its new temperature, and carefully measure its increase in length, we may then compute — (1) the number of degrees through which the solid has been warmed, (2) the increase in length for 1° change in temperature, and finally (3) *a number which expresses the ratio between the original length and the increase in length for* 1°, or, in other words, *a number which expresses the increase in length per unit length for* 1° *change in temperature.* This number is an important quantity, known as the *coefficient of linear expansion* (*or contraction*).

The accompanying table gives the coefficient of linear expansion of some common substances determined by means of the centigrade thermometer. The cubical coefficients of expansion may be taken as three times the linear coefficients.

Aluminum	.0000231	Platinum	.0000089
Brass	.0000187	Steel (Annealed)	.0000109
Copper	.0000168	Zinc	.0000297
Iron (Soft)	.0000121	Ebonite	.0000842
Lead	.0000292	Glass	.0000088

115. The Use of the Coefficient of Linear Expansion. — Practically all solids always expand with a rise in temperature, and the pressure they exert against any body which opposes this expansion is very great. This can readily be appreciated from the fact that to prevent them from expanding, we must exert as much pressure as would be necessary to bring them back to their original length after the expansion has taken place. Hence when two or more different materials are used in the manufacture of any article, which in its use is subject to considerable changes in temperature, it is often important that

these materials should have the same coefficient of expansion, otherwise serious bending or breaking is liable to occur. A familiar example of this is found in the manufacture of pottery. If the glaze or glassy coating of a dish has a coefficient of expansion different from that of the body of the dish, a change in temperature is likely to be followed by a cracking or chipping of the glaze.

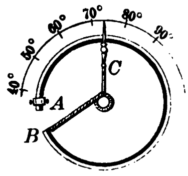


FIG. 201.—Shows the principle used in the metallic thermometer. The dark line represents the iron.

On the other hand, the unequal coefficients of expansion of brass and iron are involved in the working of a metallic thermometer.

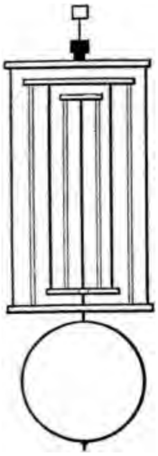


FIG. 202.—Compensation "gridiron" pendulum. The single black lines represent iron rods; the double lines brass ones.

The one end A of a compound bar is fixed, and the changes in the curvature of the bar move the free end B, which in turn, by means of a cord and pulley, moves a pointer C over a graduated dial, thus showing the changes in temperature (Fig. 201). Similarly, in clocks and watches those changes in their rate of motion, which would accompany any change in their temperature if one metal were used, are prevented by the use of a pendulum or balance-wheel composed of brass and iron arranged in such a manner that the greater expansion of the brass counterbalances the expansion of the iron (Figs. 202 and 203). Such pendulums or balance wheels are said to be compensated.

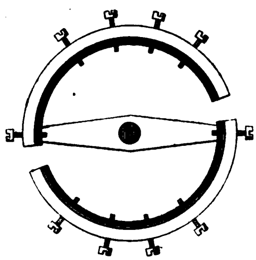


FIG. 203.—Balance-wheel of a watch; the inner portion of the rim is iron; the outer is brass.

The original length and the change in temperature of a body being known, we may also use the coefficient of linear expansion to compute its length after it has been heated or cooled.

Plainly the amount of change in length which any solid undergoes when its temperature changes, depends upon three things:

(1) The original length of the body, (2) its coefficient of expansion, and (3) the number of degrees it is warmed or cooled. For example, if the original length of a bar of lead is 1200 cm., its coefficient of linear expansion .000029, and if it is warmed from 10° to 30° C., the increase in length will be: 1200 cm. × .000029 × 20 = .696 cm., and the total length will be 1200.696 cm. at 30° C.

Platinum is the only metal that has practically the same coefficient of expansion as glass, hence platinum must always be used when an electric current is to be conducted by a wire sealed into the walls of an air-tight globe, as is the case in the familiar incandescent electric light.

Some General Applications of Expansion and Contraction of Solids. — Metal tires and bands are generally made somewhat smaller than the object they are to surround, and then put on when very hot in order that, by their subsequent contraction, they may fit tightly. For similar reasons the rivets in boilers and other metal work are generally put in when red hot.

Since the pressure produced by expanding solids is extremely large, often amounting to tons per square inch, provision must frequently be made to permit free motion, otherwise disastrous bending or breaking might follow. Telegraph wires, strung in summer, must have a considerable sag between the poles; railroad rails, unless the curves are frequent, generally have a provision at the joints for this change in length, suspension and other metal bridges, even cement walls and floors, must be provided with some degree of freedom of expansion, or breaking and cracking may occur. Soft and porous solids, like wood, frequently provide for their own expansion by a yielding of the material. On the other hand, a rigid substance, especially if it is a poor conductor of heat, is likely to break if suddenly

heated or cooled at one place, unless the material is very thin. A thick glass tumbler breaks when put into a flame.

Questions and Problems

1. Two steel rails, 20 ft. and 60 ft. long, respectively, are lying in contact with each other and the sun is shining upon them for say 1 hr.
   (*a*) The one will increase in length about how many times as much as the other?
   (*b*) Why may we assume that they will undergo the same change in temperature? How could we test it?
   (*c*) While undergoing this equal change in temperature prove that each expands the same fraction of its original length that the other does.
   (*d*) Prove that the expansion of each for 1 degree rise in temperature is the same fraction of its original length and give the proper name to this fraction.
   (*e*) Determine whether the fraction referred to in (*d*) will have the same value whether the temperature is found by a centigrade or by a Fahrenheit thermometer.

2. What measurements of length and what temperature records would be required in order to compute the linear coefficient of expansion of a body? Should we obtain the same result by using either of the rails mentioned in problem 1? Why?

3. Explain what is meant by the statement that the coefficient of linear expansion of glass is .0000089.

4. A bar of aluminum is 200 cm. long at 0° C. Find (*a*) the amount it will increase in length for each degree it rises in temperature, (*b*) the length of the bar at 25° C.

5. Compute the coefficient of linear expansion of a solid which is 654.00 cm. long at 0° C. and 654.55 cm. long at 100° C.

6. What effect does expansion always have upon the density of a body? Contraction? Name an important exception to the general rule that expansion accompanies a rise in temperature (see sec. 117). Name an exception to the rule that a rise in temperature is accompanied by a decrease in density.

7. If a platinum meter rod is correct at 0° C., find its length at 120° C.

8. A copper wire is 180.2 ft. long at $-8°$ C.; what will be its length when warmed to 37° C.?

9. If a clock pendulum is constructed by a combination of brass and iron rods of different lengths so that the expansion of the brass neutralizes the expansion of the iron, find how long a rod of iron will be required to neutralize the expansion of a brass rod 26.8 cm. long.

10. One span of a steel bridge is 300 ft. long. **Find its variation** in length when the temperature changes from 5° F. to 86° F.

11. A rod of copper and a rod of zinc are each 600 cm. long at 0°. Find which will be longer, and how much, at a temperature of 60° C.

116. The Expansion of Liquids. — By means of a glass tube, of small diameter open at both ends, passed through a cork into a flask or large test tube filled with a liquid we may show the expansion of liquids (Fig. 204).

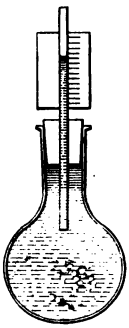


FIG. 204. — Any liquid in the flask will expand as it gets warmer excepting water between 0° and 4° C.

It is worth noting here that the rise in temperature produced by one's hand is not sufficient to cause an appreciable expansion in a liquid. When a flame first strikes the flask, the liquid sinks in the tube; but if the heating is continued, it soon begins to rise. The slow but steady rise of the liquid as it gets warmer shows that the coefficient of expansion of the liquid is larger than that of the glass and that the sinking of the liquid at first was due to the fact that the glass, being heated first, expanded first. Similarly the rise of the mercury in a thermometer which accompanies a rise of temperature proves that mercury has a larger coefficient of expansion than glass.

The Change in the Density and Pressure of Expanding and Contracting Liquids. — One of the most important effects of the expansion of liquids is the change thus produced in their densities, and consequently in their weight pressure. A given barometric height, for example, does not indicate exactly the same pressure when there has been a change in the temperature of the mercury. It will be seen later that this change in density is an important factor in the production of the circulation of any liquid while it is being heated or cooled.

The pressure produced by an expanding liquid is very great, for as previously stated, liquids are so difficult to compress that we commonly treat them as incompressible. It is well known

that a thermometer quickly bursts when the expanding liquid reaches the top of the tube.

117. The Exceptional Expansion and Contraction of Water. — Generally speaking, water expands and contracts in the manner common to all liquids, but between the temperatures of 0° and 4° C. (32° and 39° F.), it presents a remarkable and most important exception. If water at the freezing point is warmed its volume steadily decreases, with its rise in temperature, until 4° C. (39° F.) is reached, but when it is further heated, water expands, as other liquids do, up to its boiling point (Fig. 205). Of course, when cooled, water always contracts, excepting when being cooled between the temperatures of 4° and 0° C. The importance of this lies in the fact that the expansion or contraction of a liquid changes its density, and, as we have found, the density of a liquid is an important factor in its weight pressure. On account of its exceptional contraction and expansion, water is densest at a temperature of 4° C. (39° F.), and not at its own freezing point as is the case with other liquids. As cold weather approaches, the water in a pond, cooling as it always does at the free surface, contracts, becomes denser, sinks, and thus drives up the warmer water beneath. Thus a circulation will take place in the cooling water until the temperature of 4° C. (39° F.) is reached. As the water cools below 4° C., it expands and, becoming less dense, no longer sinks, but forms a layer of cold water on the top.

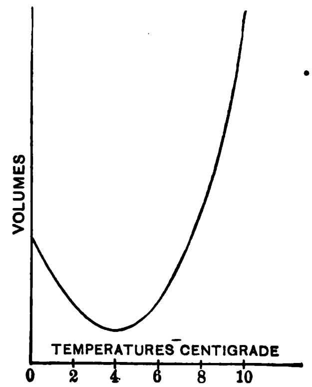


Fig. 205. — Graph showing expansion of water as the temperature is changed.

This gradual expansion of the water at the surface continues until the freezing point, 0° C. (32° F.), is reached, when, as it

solidifies, a sudden and very considerable expansion takes place. For this reason ice is less dense than water, and lakes, ponds, and streams of deep water do not freeze from the bottom upward. The part of the water which is completely frozen then contracts on further cooling as other solids do. The layer of ice and the water being poor conductors of heat, any rapid cooling of the water below is prevented. Much of the water remains at a temperature of 4° C., hence fish and other animals which would be killed by a temperature at or below the freezing point, can live in the deep water.

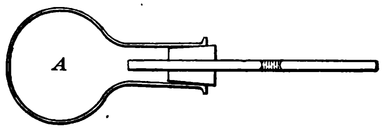


FIG. 206. — The expansion of the gas in *A* is shown by the motion of the drop of water in the tube.

118. **The Expansion of Gases.** — A flask of thin glass with an open tube passing through a tightly fitting stopper, or indeed any apparatus suitable for showing the expansion of liquids, may be used to show the expansion of gases. But since gases are generally invisible, to show the expansion the open tube must either contain a quantity of water or be thrust beneath the surface of water in a vessel (Fig. 206, or 207). If the apparatus contains air at the temperature of the room, the small change in temperature produced by holding the flask or bulb in the warm hand is sufficient to show a considerable expansion, while with liquids it produces no appreciable effect, thus showing that air has a much larger coefficient of expansion than liquids.

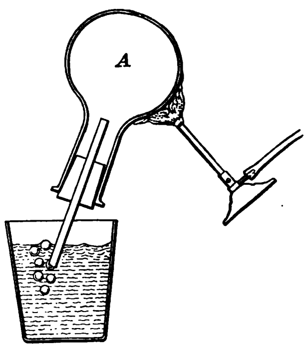


FIG. 207. — The expansion of the gas in *A* is shown by the bubbles escaping in the tumbler of water.

Since fluids have no fixed dimensions, it is quite evident that with gases as well as with liquids, only their volume or cubi-

cal coefficient of expansion can be considered. Though solids and liquids differ greatly as regards their coefficients of expansion, all gases expand practically alike.

The *coefficient of expansion of every gas is* .00366 *or* $\frac{1}{273}$ *of its volume at* 0° *C. for each* 1° *C. rise in temperature.* But because the volume of a given mass of any gas depends upon the pressure as well as upon its temperature (see Boyle's law), a more exact statement of the effect produced by any temperature change is found in the following, known as *Charles's law:*

When a given mass of any gas is under a constant pressure, the volume of the gas increases $\frac{1}{273}$ *of its volume at* 0° *C. for each* 1° *C. rise of temperature.*

Similarly, if the pressure is kept constant, the volume of a fixed mass of the gas will also decrease $\frac{1}{273}$ of its volume at 0° C. for each 1° C. fall in temperature.

119. **The Change in the Pressure of a Gas when its Temperature changes and its Volume is kept Constant.** — If a given mass of any gas is kept at a constant volume, while it is being heated or cooled, the gas increases or decreases its tension, or pressure upon the walls of the containing vessel. For each 1° C. rise or fall in temperature a gas at a constant volume changes its pressure $\frac{1}{273}$ of the amount which it exerted when at 0° C. This quantity, known as the *coefficient of the change in pressure of a gas at constant volume* is used in the gas thermometer as already suggested.

120. **Absolute Zero and Absolute Temperature.** — If the rate of contraction of a cooling gas, as expressed by Charles's law, could continue indefinitely along with the fall in temperature, plainly the volume of the gas would vanish at a temperature 273° below 0° or −273° C. Or if we consider the decrease in pressure which takes place with the fall in temperature, it follows that a gas cooled 273° below 0° C. would exert no pressure. The molecules of the gas, being no longer able to exert

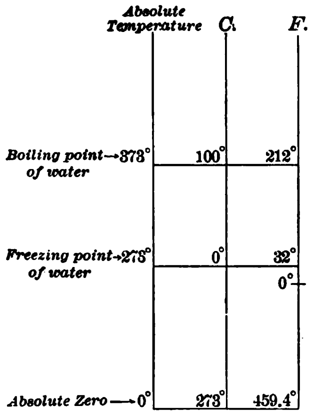


Fig. 208. — Shows the relation between the absolute, the centigrade, and the Fahrenheit scales.

a pressure against the containing vessel, must be at rest, — the body is heatless. These considerations suggest that $-273°$ C. is probably the *absolute zero.* No one has ever succeeded in depriving a body of heat or cooling it to the absolute zero, though some experimenters have come within about 9° or 10° of it. All gases, with the possible exception of the rare gas helium, liquefy before reaching the absolute zero, and after they become liquids they no longer contract according to Charles's law.

If we select the absolute zero as the starting point in reckoning temperature, and use centigrade degrees as our temperature units, the number which then expresses the temperature of a body is called its *absolute temperature* (Fig. 208). Since the centigrade zero is 273° above the absolute zero, the absolute temperature of any body is found by adding 273° to its centigrade temperature. Thus the temperature of melting ice and boiling water are respectively 273° and 373° on the absolute scale. The law of Charles may now be stated as follows: *when a given mass of any gas is under a constant pressure, the volume of the gas varies directly as its absolute*

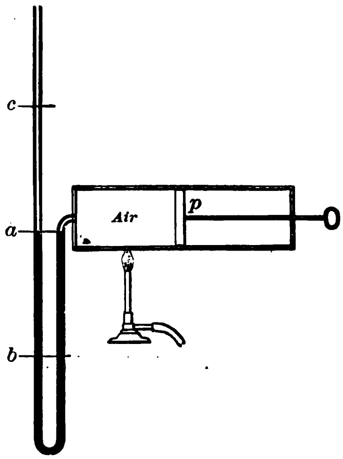


Fig. 209. — If the air is heated and the piston kept from moving, the *pressure* increases as the absolute temperature. If the piston is moved so as to keep the pressure constant, the *volume* of the air increases as the absolute temperature.

temperature (Fig. 209). The symbol t is commonly used to indicate the centigrade and T the absolute temperature of a body, hence $T = t + 273°$.

121. Law connecting the Pressure, Volume, and Temperature of Any Gas. — It was shown, in section 39, that the volume (v) of a given mass of any gas, at constant temperature (t) varies inversely as the pressure (p) upon it, hence $p \times v$ has a constant value (Boyle's law). It has just been shown that the volume of any gas under a constant pressure varies directly as its absolute temperature (T), hence $\frac{v}{T}$ has a constant value (Charles's law).

By a combination of these two laws we may find an expression for the change in volume when the pressure and the temperature both vary. Because when T is constant v varies inversely as p, and when p is constant v varies directly as T, it follows that when p and T both vary, v varies as $\frac{T}{p}$ and then $\frac{pv}{T}$ has a constant value.

This means that the product of the pressure and volume of a given mass of any gas, divided by its absolute temperature always gives the same quotient, no matter what changes in pressure or temperature the gas may undergo. If v_1, p_1, T_1, represent the volume, pressure, and absolute temperature of a gas at any time, and v_2 p_2 T_2, the volume, pressure, and temperature of the same gas at another time, then

$$\frac{v_1p_1}{T_1} = \frac{v_2p}{T_2} \text{ or } \frac{v_1p_1}{273° + t_1} = \frac{v_2p_2}{273 + t_2}$$

since $T = 273° + t$.

Any five of the six variables in this equation being known, we may find the sixth.

For example, if a chemist finds that a certain mass of gas has a volume of 1600 c.c. when under a barometric pressure of 70 cm. and at a temperature of 12° C., and he wishes to know

its volume when the barometric pressure is 75 cm. and the temperature is 27°, he substitutes in the equation as follows:

$$\frac{70 \times 1600}{273+12} = \frac{75 \times v_2}{273+27}$$

Solving, he finds the value of v_2 the second volume to be 1571.9 + c.c.

1. A certain mass of air has a volume of 273 c.c. at 0° C. The pressure being constant, what will be its volume when it is warmed to 1° C.? When it is warmed to 40° C.?

2. If the pressure is constant, how many degrees must 1 c.c. of air be warmed to double its volume? The same mass of air will have what volume at – 63° C.?

3. If air is heated and not allowed to expand, what change occurs? State the law which shows the connection between this change and the change in temperature.

4. A bicycle tire is filled with air at standard atmospheric pressure and at 0° C., and subsequently the air is warmed to 91° C. Assuming that the tire does not expand, the second pressure will be how many times the first? Express the second pressure in terms of the height of the mercurial barometer.

5. A liter of dry air weighs 1.293 gm. at standard pressure and 0° C. Find the weight of a liter at standard pressure and a temperature of 20° C.

6. Find the volume at 60° C. of a certain mass of gas which has a volume of 300 c.c. at 180° C., the pressure being constant.

7. State Boyle's law. Find the weight of a liter of air at a temperature of 20° and a pressure of 70 cm. as indicated by the barometer. (See problem 5.)

8. A quantity of coal gas has a volume of 500 c.c. at 10° C. and 75 cm. pressure. Find its volume at 20° C. and 80 cm. pressure.

9. If in breathing a man always expands his lungs to the same extent, will he take a greater weight of air into them when the pressure is high or when it is low? When the temperature is high or low? When at the sea level or when on a mountain? In summer or in winter?

The Changes of State produced by Heating and Cooling

122. Tracing the Possible Changes. — Let us suppose that when a thermometer is placed in contact with a piece of ice

which has just been brought indoors on a cold winter day it records a temperature of $-10°$ C. If heat be given to the ice, its temperature will rise, but no part of it will melt until the thermometer in contact with that part shows $0°$ C., or the melting point. If we continue to give heat to it, no matter how rapidly, the unmelted portion will not get any warmer than $0°$ C. The heat which enters is now melting the ice; that is, doing the work of changing the state from solid ice to liquid water.

After the ice is all melted the thermometer shows a rise in temperature, as more heat is given to the water, until finally the boiling point or $100°$ C. is reached. If we continue to furnish heat to the water, the thermometer in it no longer rises, showing that the heat given to water at its boiling point is being used to do the work required to change the water from a liquid state to the gaseous or vapor state, called steam. After all the water has undergone this change of state, a further addition of heat to the vapor or steam in a closed vessel will then produce a rise in temperature of the steam.

Let us next suppose that heat is being removed from a quantity of very hot steam and trace the changes. As it loses heat the temperature of the steam will fall until the boiling point $100°$ C. is reached, but will then remain constant as the steam or water vapor gradually passes into the liquid state. After practically the whole mass of steam is changed into the liquid state, then the continued removal of heat again cools the water until finally the freezing point, $0°$ C. is reached, where again the removal of heat results in a change of state without a change of temperature, this time from the liquid to the solid state. After all is frozen, a further removal of heat would lower the temperature indefinitely.

Many other substances will go though a series of changes which are similar to those just traced for water. Having formed a fairly definite picture of the possible changes of state, we now propose to consider each more fully.

123. The Change from a Solid to a Liquid State; Melting; Fusion. — Many solids can be changed into the liquid state by a mere addition of heat, the process being called melting or fusion. The temperature at which any substance undergoes this change of state is called its melting point. The tissues of plants and animals, such as wood and muscle, are familiar examples of substances which cannot be melted because they undergo chemical changes at comparatively low temperatures.

Many substances do not definitely and suddenly pass into a liquid state as water does, but instead they gradually lose the characteristics of a solid and acquire those of a liquid. Pitch and coal tar are examples of such substances.

The change from a liquid to a solid state is the reverse of melting. This process is called freezing or solidifying. It occurs at the same temperature as melting, hence the melting point and the freezing or solidifying point are for a given substance identical.

Careful experimenting has established the following laws of melting for crystalline substances.

1. Each crystalline substance, if pure and under a constant pressure, has a fixed melting point.
2. The unmelted portion of the substance has a constant temperature until all is melted.
3. A substance which expands while melting has its melting point slightly raised by increased pressure, and one which contracts on melting has its melting point lowered by increased pressure.
4. The presence of an impurity, if soluble, always lowers the melting point.

The bursting of water pipes when water freezes in them is a familiar proof of the fact that water expands while solidifying, hence contracts as it melts. The pressure exerted by the freezing and expanding water is enormous, sufficient to break a vessel of almost any strength or to fracture the strongest

rocks. Because ice contracts when melting, an increased pressure lowers the freezing or melting point. This is shown when a quantity of broken ice or snow crystals are tightly packed together in a ball. The increased pressure at points of contact melts the ice slightly and the release of the pressure is followed by a freezing which joins the crystals together. The same fact is nicely shown by hanging weights on the ends of a wire which rests upon a piece of ice as shown in Figure 210. The wire, by its pressure, lowers the melting point of the ice underneath, and thus melts its way through the ice, the particles of water freezing again above the wire as the pressure is released.

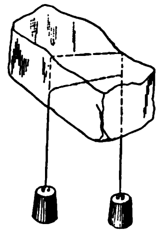


FIG. 210. — On account of its pressure the wire melts its way through the ice.

124. The Heat required to melt or dissolve a Substance; the Heat of Fusion. — A thermometer placed in a melting substance shows no rise of temperature if the melted and unmelted parts are kept thoroughly mixed. Heat is entering the substance but it is not warmed. That a large quantity of heat enters a melting substance without warming it can readily be shown by putting equal weights of ice and ice cold water into similar vessels and placing both vessels into a dish of hot water (Fig. 211). Though at first both have the temperature of 0°, and both receive heat at about the same rate from the surrounding water, the liquid water gets warmer, but the ice does not. The heat entering the ice is used to do the work of melting — it changes the state of the substance. Similarly, if a quantity of salt or sugar is dissolved in water, which is at first at the temperature of the room, a thermometer will show that the water must have given up some of its heat to dissolve or liquefy the solid.

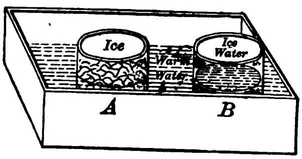


FIG. 211. — While the ice in A is melting, an equal amount of heat will warm an equal mass of water in B through 80° C.

Accurate experiments show that the quantity of heat which is required to melt 1 gm. of ice would warm 1 gm. of water from 0° to 80° C. Hence the *heat of fusion* (sometimes called latent heat) of ice is 80 gram calories for each gram of ice. Other solids also have their heats of fusion. The heat of fusion of any solid is the number of gram calories which must be given to each gram of the substance to convert it into a liquid, after the solid has reached its melting point. Conversely, when any cooling substance has reached its solidifying point, the same quantity of heat must be removed from each gram of the substance to convert it into the solid state as must be added to each gram of the solid to melt it. In this case also no temperature change occurs.

For example, water as it freezes must give off 80 calories per gram of water frozen, but the removal of this heat does not lower its temperature. For this reason the freezing of large bodies of water or the forming of large quantities of snow, on account of the large amount of heat given out in freezing, prevents the average temperature of the surrounding air from becoming as low as it otherwise would. On the other hand, with the coming of warmer weather large quantities of heat are required to melt this ice and snow, which heat would otherwise warm the air, hence the large heat of fusion of water exercises an important influence in preventing the sudden coming of either cold or warm weather.

TABLE

THE MELTING POINTS AND HEAT OF FUSION OF SOME SUBSTANCES

SUBSTANCE	FUSION POINT	HEAT OF FUSION
Mercury	– 39° C.	2.8
Water	0°	80.
Lead	326°	5.9
Iron (cast)	1100° – 1600°	23 – 33

125. The Application of the Cooling Effects of Melting and Dissolving. Freezing Mixtures. — A mixture composed of finely powdered ice or snow with about one half its weight of common salt cannot remain in the solid state at any temperature above the freezing point of the mixture, about $-20°$ C. But, as shown in the discussion of "heat of fusion," all solid bodies require heat to convert them into the liquid state, whether they are undergoing this change by the process called melting or that called dissolving. In some cases, the melting ice and salt take the needed heat from the surrounding bodies, such as cream placed in a good conducting metal can. If the surrounding bodies do not furnish heat rapidly enough, portions of the solids will melt by taking their heat of fusion from the remainder, and thus the temperature of the whole mass is lowered. Such a mixture, which may consist of quite a variety of solids or of solids and liquids, is frequently called a *freezing mixture*. Upon the principle of freezing mixtures depends the working of the familiar ice cream freezer (Fig. 212), and the melting of ice and snow on sidewalks by the use of salt.

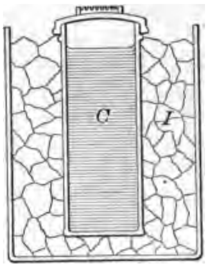


FIG. 212. — The ice and salt at *I*, in order to procure the heat required to change them to the liquid state, take enough heat from the cream *C* to change it to the solid state.

1. A piece of ice is floating for a time in warm water; does the water lose heat? Does the ice receive heat? Does the temperature of the water change? Does the temperature of the ice change? Explain.

2. What is the meaning of the statement that the heat of fusion of lead is 5.9? Does the kind of thermometer used have any effect upon the number known as the heat of fusion of a substance? Why?

3. How much heat is required to melt 10 gm. of ice? 10 gm. of silver?

4. When ice is forming on a pond what heat change is occurring in the part of the water that is changing its state? Does the water become any colder on account of this heat change? What is the source of the heat energy? What becomes of the heat?

5. How many grams of ice must be put into 250 gm. of water at 60° C. to lower its temperature to 20° C., considering only the heat furnished by the cooling of the water and the heat of fusion of the ice?

6. If 120 calories of heat are given to 1 gm. of ice at 0° C., find the temperature of the water produced by the melting. Trace the changes of volume from the time the ice begins to melt until the final temperature is reached.

7. Explain why a given mass of ice at 0° C. is more effective in reducing the temperature within a refrigerator than is an equal mass of liquid water at 0° C.

8. If the final temperature is 20° in both cases, the cooling effect of 1 lb. of ice would be equal to that of how many pounds of water at 0°?

9. A brass calorimeter weighing 40 gm. contains 200 gm. of water. If 60 gm. of ice are put into the water, the resulting temperature is 10°. Find the original temperature of the water and calorimeter.

126. The Change of a Liquid, occasionally of a Solid, to a Gas or Vapor. — Most liquids may be converted into the gaseous or vapor state by the addition of heat. This change of state, without regard to the conditions under which it occurs, is called *vaporization*. Any substance, which at ordinary temperatures and pressures exists chiefly in the solid or liquid state, is called a vapor after it has been converted into its gaseous state. Familiar examples of such substances are water, alcohol, benzene, gasoline, sulphur, and camphor. Oxygen, hydrogen, illuminating gas, and air are familiar examples of substances which are never in the liquid or solid state except at such low temperatures and high pressures as never occur naturally, hence we do not call them vapors. This distinction between gases and vapors, though not complete, is sufficient for our purpose.

If the formation of a vapor takes place *at the free surface only* and through quite a wide range of temperature, the process is known as *evaporation*.

When the same change of state consists in the formation of bubbles of vapor in any part of the liquid to which heat may be given, and when under fixed conditions it occurs at a constant temperature, the process is known as *boiling or*

ebullition. We shall now discuss these two methods of vaporization separately.

127. Evaporation; a Change to Vapor or Gas occurring at the Free Surface only. — When an open vessel of water stands upon a table for an indefinite length of time, the quantity of water gradually decreases until it entirely disappears.

After a rain the ground and sidewalk gradually become dry. In these familiar processes the evaporating water passes off at the free surface as an invisible vapor. Other liquids also evaporate, but do they all evaporate at the same rate and does any one liquid evaporate at a constant rate under all conditions? We can readily answer the first of these questions by selecting, say 1 c.c. each of kerosene, water, alcohol, and gasoline, and placing each in a common tumbler and noting the time required for each to evaporate completely. The second question may be answered (1) by placing equal quantities of alcohol or water in two vessels, one of which is tall and narrow like a test tube, and the other broad and shallow like a dinner plate, (2) by using equal quantities of the same liquid in like vessels but putting one in a warm and the other in a cool place, and (3) by using equal quantities of the same liquid in like vessels so as to keep them equally warm, but putting one vessel in a draft of air. Careful experimenting has established the following laws of evaporation:

(1) The rate of evaporation depends upon the substance used.

(2) The rate of evaporation of a given substance increases with the amount of its free surface.

(3) The rate of evaporation of a given substance increases with an increase of its temperature.

(4) The rate of evaporation of any substance is increased by the prompt removal of the vapor already formed.

A few solids, notably ice, snow, and camphor, evaporate slowly at ordinary temperatures, while others, for example iodine crystals, vaporize at higher temperatures without melting.

128. Evaporation and the Kinetic Theory of Matter. — A study of evaporation in connection with the molecular theory is mutually helpful to an understanding of both. If the most powerful microscope were directed to the surface of an evaporating liquid we could not see the particles of the vapor leaving the liquid.

A vapor must therefore pass away in exceedingly small particles, probably as individual molecules. In the fact that an increase in temperature increases the rate of evaporation, we find good evidence in support of the kinetic theory of matter and the accepted theory of heat; for these theories assert that the molecules of a body are always in motion, and that they move faster when the heat energy and temperature of the body are increased. According to this view it is easy to see why the molecules escape more rapidly at the free surface as the temperature of the liquid rises.

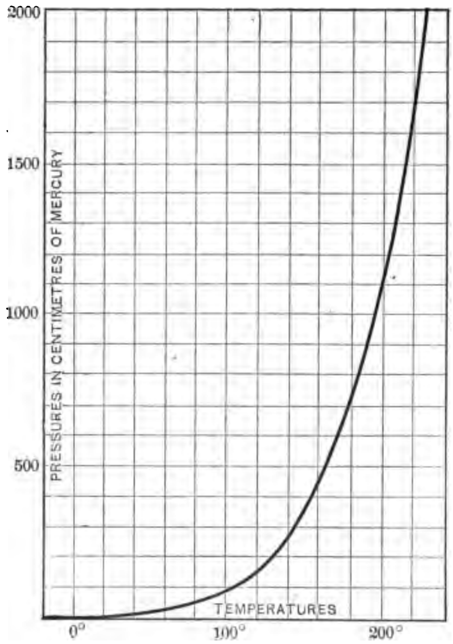


FIG. 213. — Graph showing the connection between the temperature and pressure of saturated water vapor.

Because the removal of the vapor from an evaporating liquid facilitates the evaporation, we conclude that the back pressure of the vapor in contact with the free surface interferes with the escape of other molecules from the surface. In fact, for every liquid, *when a certain vapor pressure is reached, no more evaporation can occur unless the temperature is raised.*

When the space above the liquid is so filled with the flying molecules of its vapor that their number cannot be increased without raising the temperature of the liquid, *the space is said to be saturated,* and the vapor pressure is then the greatest possible for that temperature (Fig. 213). For example, the upper half of a bottle which is half filled with alcohol soon becomes a space saturated with alcohol vapor and evaporation ceases. If the bottle is opened and the vapor removed, either slowly by its own molecular motion or rapidly by the use of a pump, the vapor pressure is reduced and evaporation is resumed.

129. Boiling and the Boiling Temperature. — If heat is given to a liquid at or near its freezing point, it undergoes a rise in temperature, usually accompanied by some evaporation, as already explained. With many liquids, such as water and alcohol, a temperature is finally reached when a process of vaporization begins which is rapidly and definitely visible. Bubbles of vapor form within the liquid at whatever points it receives the heat, and these bubbles as they rise through the liquid are easily seen. If the containing vessel is open, the temperature of the liquid, called its *boiling point,* remains constant until the liquid is all vaporized — "boiled away." If a flask of boiling water containing a thermometer is placed under the receiver of an air pump or is arranged in any way so that the pressure upon the surface of the boiling water may be decreased, the thermometer shows that the water boils at a temperature far below 100° C. (Fig. 214). Indeed with proper appliances the boiling point may be lowered to approximately 0° C. The reason for this lies in the fact that the volume of the vapor is much larger than that of the same mass of liquid.

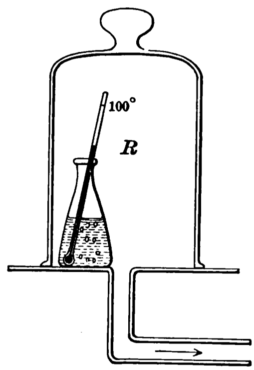


FIG. 214. — On account of the reduced pressure in *R*, the water boils much below 100° C.

It is evident that the bubbles are formed in opposition to the external pressure, hence they form at a lower temperature when this pressure is reduced.

Another method of showing the same relation between pressure and the boiling point is known as Franklin's experiment. A round-bottomed flask, about half full of water, is heated until the water boils rapidly and the water vapor or steam displaces the air. If the flask is tightly corked while the water is boiling and the flask quickly removed from the source of heat, it now contains nothing but liquid water and water vapor. If the flask is then inverted and cold water or ice is put upon the top (Fig. 215), some of the water vapor at V is immediately converted into liquid water, and the pressure is thus reduced. On account of the reduced pressure upon it the water then boils, producing new water vapor.

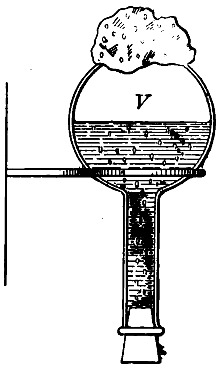


FIG. 215. — As the condensation of the water vapor at V reduces the pressure, the water boils.

Because of the effect of pressure upon the boiling point, water on a high mountain, where the atmospheric pressure is low, may boil far below 100° C., even below the temperature necessary for cooking. On the other hand, the boiling point within a high-pressure steam boiler may reach 150° C., or even more.

By careful experimenting on many liquids the following laws of boiling have been determined:

1. The boiling point depends on the kind of liquid.

2. The boiling point of any liquid rises with an increase of the pressure upon it, and falls with a decrease of the pressure.

3. The boiling point of a liquid is raised by dissolving a solid, and lowered by dissolving a gas in the liquid.

4. The character of the vessel slightly affects the boiling point within the liquid, but not the temperature of the vapor

immediately above it. (For table of boiling points see section 133.)

130. **The Condensation of Vapors and the Liquefaction of Gases.**—It is a familiar fact that a piece of cold glass, held in the saturated air exhaled in breathing, or held in the vapor laden air above a vessel of boiling water, soon becomes coated with a layer of liquid water. If the piece of glass is considerably below the freezing point, breathing gently upon it may result in the formation of a layer of water in the solid form which is essentially the same as frost. In all these cases, a portion of the water vapor contained in the air undergoes a change from the vapor to the liquid or solid state. *This change of state, called condensation, is the reverse of vaporization.* Condensation must not be confused with compression, or the increase of density which occurs when a gas is subjected to increased pressure, sometimes unfortunately called "condensing" the gas.

When a gas, for example air, is changed to the liquid state, the term *liquefaction* instead of condensation is used to express the change. Both vapors and gases may be changed into the liquid state by cooling, that is, by the removal of heat alone, provided they are cooled sufficiently. On the other hand an increase of pressure upon an unsaturated vapor or on a gas merely raises the temperature at which the condensation or liquefaction will begin. Hence, when we wish to liquefy a gas, in order to avoid the necessity of reducing its temperature to an extremely low degree, we increase the pressure upon it, in some cases to even a hundred "atmospheres" or more. For example, carbon dioxide gas at the standard atmospheric pressure, may be liquefied by cooling it to about $-80°$ C., but when it is placed under a pressure of 73 atmospheres it will liquefy at $31°$ C.

131. **The Critical Temperatures of Gases.** — Though an increase of pressure raises the temperature at which a gas will begin to liquefy, *there is a particular temperature for each gas*

above which no amount of pressure will convert it into a liquid. This is called the *critical temperature* of the gas. For example, no amount of pressure will serve to convert air into a liquid above −140° C., its critical temperature, and at that temperature it requires about 39 atmospheres of pressure. If, however, air is cooled to −182° C., it will liquefy at the ordinary atmospheric pressure. From this it follows that the boiling point of liquid air is −182° C. at standard barometric pressure. But because the critical temperature of ammonia gas is 130° C., it may be liquefied at ordinary air temperatures by merely increasing the pressure upon it. To liquefy ammonia at the standard atmospheric pressure it must be cooled to −38°, that is, to its boiling point (see table, sec. 133).

TABLE

Substance	Critical Temperature	Pressure required at Critical Temperature
Water	365° C.	200 atmospheres
Alcohol	243°	63 "
Ammonia	130°	115 "
Oxygen	− 119°	50 "
Nitrogen	− 146°	34 "
Air (a mixture)	− 140°	39 "

132. **Distillation.** — When any liquid or a mixture of liquids is vaporized and the vapor afterwards condensed by cooling, the entire process is called distillation. It may readily be accomplished by heating the liquid, for example, muddy salt water, in a closed vessel *A* (Fig. 216) from which a tube *B* carries off the water vapor or steam. The tube is surrounded by a larger tube *C* containing running cold water, and the vapor is condensed and appears as pure liquid water at the open end of the tube *B*. The mud and salt, because they do not vaporize, remain behind in the vessel *A*.

The chief uses of distillation are (1) the separation of a liquid from a solid which is dissolved in or mixed with it. Fresh water is thus prepared from sea water. (2) When two or more liquids with different boiling points are mixed, they may be separated partially by heating the mixture first to the lowest boiling point, then to the next, — collecting and condensing the vapors as they come off at their respective boiling points. In this manner the mixture known as crude petroleum is

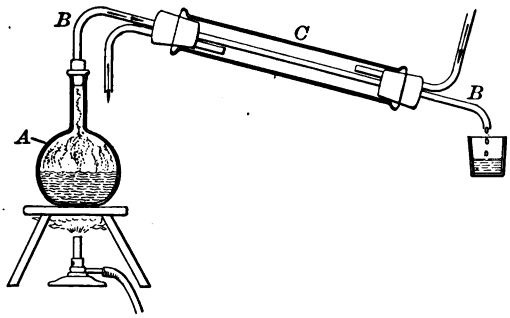


FIG. 216. — Distillation. The vapor produced in A in condensed in B.

separated into a number of decidedly different substances, such as gasoline, kerosene, and lubricating oil.

133. **The Heat which is required to produce Vaporization or the Heat which is generated by Condensation and Liquefaction.** — If a thermometer is placed in boiling water or any other liquid boiling under constant pressure, it will be found that the temperature does not change. Large quantities of heat energy are going into these boiling liquids, but because they are not warmed the heat must be doing the work of changing the liquids into the vapor state. Similarly, when water, alcohol, or other liquids evaporate rapidly, a thermometer, or sometimes the hand, will show that heat energy is being used to do the work of evaporation. This is similar to the "heat of fusion" or the heat required *to melt a solid.*

TABLE

The Boiling Point and Heat of Vaporization of Some Common Substances

Substance	Boiling Point under Atmospheric Pressure	Heat of Vaporization
Water	100° C.	536 gram calories
Alcohol (ethyl)	78°	209 " "
Ammonia	– 38°	295 " "
Ether	35°	90 " "
Mercury	357°	62 " "
Liquid Air	– 182°	—
" Nitrogen	– 194°	—
" Oxygen	– 184°	—

The quantity of heat which is required to vaporize any liquid, whether by slow evaporation or by the more rapid process known as boiling, is called the heat of vaporization of that liquid. Careful experimenting has determined that it requires about 536 gram calories to vaporize 1 gm. of water. But the condensation of vapors and the liquefaction of gases are processes which are the exact reverse of vaporization. Hence, for every 1 gm. of water vapor or steam converted into liquid water 536 gram calories of heat are generated. It takes 100 gram calories to warm 1 gm. of ice water to the boiling point, and 536 gram calories or over five times as much heat to vaporize or " boil it away " after 100° C. is reached. The severe scalding effect of a given weight of steam at 100°, compared to that produced by an equal weight of boiling water, is due to the large amount of heat generated by the condensation of the steam. It is plain also that most of the heat used in a steam heating system is furnished by the condensation of the steam in the radiator, and not by the mere cooling of the water as it is in a

2. How much heat is required to vaporize 1 gm. of water? 8 gm. of water? 1 gm. of ether? 12 gm. of ether? (See Table, page 206.)

3. If 16 gm. of steam at 100° C. when condensed in 400 gm. of water furnishes enough heat to warm the water to 100°, what was the temperature of the water when the steam was introduced?

4. A piece of iron at 800° C. weighing 1000 gm. is thrust into water at 100°. Will the water be warmed? How much water will be vaporized?

5. If in finding the heat of vaporization or condensation of water, steam is introduced into a vessel of cold water until the temperature is 40° C., state (1) the temperature of the steam when admitted, (2) the final temperature of the water produced by the condensation of the steam, and (3) the two different ways in which heat is furnished to warm the original water.

6. Liquid air in an open vessel surrounded by air and other bodies at the ordinary temperatures will not get warmer than about − 182° C., though it is constantly receiving heat from the surrounding bodies. Explain.

7. Why will liquid air boil when placed in a metal vessel which is standing on a block of ice? What effect will this have on the temperature of the ice?

8. Give two reasons why the scarcity of water in any large area of the earth's surface results in greater extremes of temperature than those which exist in a similar area at the same latitude where there is an abundance of water.

9. The formation of dew involves what change of state? What effect does the formation of dew have upon the temperature of the air? Why?

10. In heating a house by steam the water may leave the radiator at about the same temperature as that of the entering steam. How has the heat been furnished to the radiator?

135. The Evaporation of Water in its Relation to the Air.— Water vaporizes at its boiling point or at any temperature below it. Even ice evaporates; as we well know wet clothes "freeze dry," on a day when the temperature is constantly below the freezing point. When the temperature is low the rate of evaporation is low, and the greatest quantity of vapor which can go into, say a cubic foot of air, is small. As the temperature rises the maximum quantity of vapor that can go into a cubic foot of air increases, hence the pressure of the vapor increases (see Table). When the boiling point is reached, the

vapor pressure equals the atmospheric pressure and a certain cubic foot may contain water vapor or steam alone. If a mixture of air and saturated water vapor at 100° C. is cooled, a part of the water vapor condenses or passes into the liquid state for each degree fall in the temperature. When the freezing point is reached, a further lowering of the temperature produces a change of a part of the remaining water vapor into the solid state in the form of frost. That is, condensation is sometimes a change from a vapor to a solid state. It is not possible to remove the water vapor from air completely by merely lowering its temperature, though the quantity present is always small when the temperature is low. Neither evaporation nor condensation is produced by the air, though by its presence air diminishes the rate at which both processes occur. Heating and cooling are responsible for the changes of state. Air is a mixture of several substances in the gaseous or vapor state, any one of which may be converted into the liquid state. It is correct to think of air as *having* water vapor, but not as *holding* or supporting vapor as it supports dust, clouds, and other liquid or solid particles.

TABLE

THE WEIGHT OF WATER VAPOR CONTAINED IN SATURATED AIR

(1 GRAIN = .064 + GM.)

TEMPERATURE F.	GRAINS PER CU. FT.	TEMPERATURE F.	GRAINS PER CU. FT.
20°	1.321	60°	5.745
25°	1.611	65°	6.782
30°	1.956	70°	7.980
32°	2.113	75°	9.356
35°	2.366	80°	10.934
40°	2.849	85°	12.736
45°	3.414	90°	14.790
50°	4.076	95°	17.124
55°	4.849	100°	19.766

136. Saturated Space — Saturated Air; Dew-point. — As previously shown, the greatest amount of water vapor which can exist in a cubic foot depends upon the temperature. Though there may be less than this maximum quantity present, generally speaking there can be no more. Any space, which contains all the water vapor that can go into it at a given temperature, is said to be saturated. Should the space contain air at the same time, we commonly say that the *air is saturated.* Cooling any mass of saturated air will result in the immediate liquefaction or condensation of a part of the water vapor. If air be not saturated, it may be cooled for a time before condensation will begin. The particular temperature to which the air at any time must be cooled before the condensation of water vapor begins is called the *dew-point.* Sometimes the quantity of vapor present is so small that the cooling must be carried below the freezing point before the air becomes saturated, and then the dew-point or temperature at which condensation begins might more logically be called the *frost point.* For example, if the atmosphere on a certain day in summer has 7.9 gr. of water vapor to the cubic foot (see Table), and the thermometer stands at 90° F. at sunset, the air in contact with the ground must cool to 70° before dew will begin to form. If, however, there are 12.7 gr. of vapor to the cubic foot, the air when cooled to 85° will reach the dew-point, or the temperature of saturation. If on a certain winter day the air contains only 1.6 gr. of vapor to the cubic foot, then the dew-point will be below 32° and condensation will not begin until the temperature falls to 25° and frost will then form.

137. Relative Humidity. — The actual amount of water vapor per cubic foot of air is a true index of its humidity, but whether the air feels "damp," "moist," "muggy," as we commonly say, depends not only on the actual amount which is then present, but also on the relation of this amount of vapor to the amount required for saturation at that time; that is,

it depends upon what is known as the ***relative humidity.*** Thus 4.4 gr. of water vapor to the cubic foot when the air is at 55° F. is about 90 per cent of the amount required for saturation (see Table, sec. 135), but if the same amount of vapor is in a cubic foot of air at a temperature of 75°, there is less than one half the maximum amount required for saturation, and the relative humidity is 47 per cent. Warming air, provided no evaporation takes place, lowers the relative, but does not change the actual humidity or the dew-point. Hence we say, warming the air "dries it." Cooling has the reverse effect. If the temperature remains constant and evaporation occurs, the relative as well as the actual humidity increases.

138. **Humidity as a Factor in Climate.** — From the discussion in the last topic it plainly follows that the rate at which water evaporates or "objects dry" when exposed to the air depends, along with other things, upon the relative humidity of the air at that time. The human body is a heat generator, transforming the potential energy of food and waste tissue into heat. Much of the excess of the bodily heat is removed by conduction to the air and other surrounding bodies. In warm weather, however, this method alone does not remove the heat fast enough. To facilitate the removal of the heat large quantities of water appear on the surface of the body as perspiration. The evaporation of this perspiration requires large quantities of heat to furnish the "heat of vaporization," thus cooling the skin. When the relative humidity is low, evaporation is rapid and the cooling effect is sufficient for the needs of the body. But when the relative humidity is high, say 80 to 100 per cent, the perspiration may come freely, but on account of the slow evaporation, the cooling effect is small and we suffer from the excess of heat. Hence a high relative humidity renders the climate of a warm season or of a warm country oppressive.

139. **Dew, Fog, Cloud, Rain, Frost, Snow.** — Water vapor is as invisible as the other constituents of pure air. When

the air near the ground is cooled to a certain temperature, the dew-point, condensation begins and very minute drops of water begin to collect on the grass and other bodies, growing larger as the condensation continues.

This product of condensation is called dew. If, however, the cooling takes place in a considerable mass of air above the ground, whether by mixing with colder air, by expansion, or otherwise, the condensation will result in the liquid water attaching itself to invisible dust particles floating in the air, and the product is now called mist, fog, or rain cloud, the term used depending upon the elevation at which the condensation occurs. In the early stages of mist, fog, and rain cloud the individual drops or globules are too small to be seen, but if they grow sufficiently large, they fall as rain.

The condensation as above described is supposed to take place at a temperature above the freezing point. Should a similar process take place below the freezing point, the product is called frost if on the solid earth, but a snow cloud when in the atmosphere. If the very minute crystals of the snow cloud grow sufficiently large, they fall to the earth, otherwise they drift with the air in which they are. *A cloud then is not water vapor, but a collection of very minute quantities of water in the liquid or solid state.*

Remembering that condensation is always accompanied by a generation of heat, the equivalent of the heat of vaporization, it follows that the formation of large quantities of dew, rain, and snow prevent the temperature of the air from going so low as it otherwise would. When the dew-point is below the freezing point, there is danger of frost even when the thermometer is considerably above the freezing point at nightfall. But if the dew-point is above the freezing point, the early formation of dew, by the heat of condensation set free, will prevent the temperature from going down to the freezing point. These facts are used by the weather bureau in predicting frosts.

Methods of Transferring Heat

140. **Conduction.** — When one end of a piece of iron wire or other metal is held in a flame, the heat travels through the metal to a considerable distance from the source. The heat travels, but the particles of the metal retain their relative positions. This method of transferring heat is called conduction. A simple explanation of conduction is found in our theory of heat. In the hottest part of any body the molecules move most vigorously. These rapidly vibrating molecules contribute a part of their energy to their neighboring molecules and they to the next, thus passing a part of the heat along the metal. An important feature of conduction is found in the fact that the heat travels but the conducting body does not. A piece of wood and a wire held in the same flame will show that all bodies do not conduct heat equally well.

TABLE

Relative Conductivities for Heat, Silver being taken as the Standard

Substance	Relative Con.	Substance	Relative Con.
Silver . . .	1.00000	Marble . . .	.005
Copper . . .	.86	Water . . .	.002
Brass . . .	.24	Glass . . .	.0005–.0023
Iron	.20	Wood . . .	.0003
Lead . . .	.08	Sawdust . .	.00012
Mercury . .	.02	Flannel . .	.00004

An inspection of the table shows that substances differ widely in their conductivity or ability to convey heat in this way. The best conductors are the metals and the poorest are gases, which scarcely conduct at all (Fig. 218).

Heat conductivity largely governs the choice of materials in

the construction of heating appliances, refrigerators, ice houses, and fireproof safes. Porous substances which contain a great deal of air are on that account usually very poor conductors of heat. The protection afforded by clothing against a too rapid loss of heat is due partly to the kind of material used and partly to the amount of air contained in its pores.

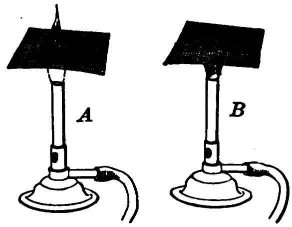


FIG. 218. — The principle of the Davy safety lamp. The wire gauze conducts the heat so well that the flame cannot get below the gauze in *A* nor above it in *B*.

141. The Relation of Conduction to Sensation. — If on a cold winter day we pick up from the ground with the bare hand a piece of wood, a stone, and a piece of iron, we say that the iron feels coldest and the wood the least cold. If we pick up the same bodies when they are lying in the sunshine of a hot summer day, we decide that the iron is the warmest and the wood is the least so. A thermometer would probably tell us that all three bodies were at the same temperature on the winter day and likewise on the summer day. When below the temperature of the hand the good conducting iron cools the hand faster than either of the other two, hence feels coldest, but when above the temperature of the hand the good conducting iron carries heat to the body fastest, hence feels hottest. On the contrary, the poor conducting wood conveys the heat to or from the hand so slowly that it does not feel either very cold or very hot even when its temperature is decidedly above or below that of the hand in contact with it.

142. Convection and Convection Currents. — If the water in a vessel is heated at the top the upper layers alone receive heat, the water very slowly conducting the heat downward. Water in a test tube may thus be raised to the boiling point at the top without materially melting a piece of ice held

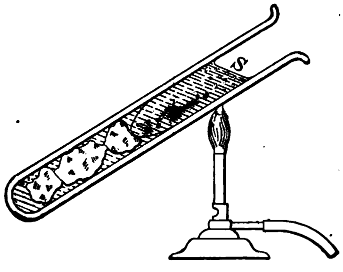


FIG. 219. — A bent wire keeps the ice from floating. The water is boiling at S.

a few inches below the surface (Fig. 219). But when the heat is applied to the bottom of a vessel, the water at the bottom expands (excepting between 0° and 4° C.) as its temperature rises. Having thus become less dense at A (Fig. 220), the colder, denser water at B now exerts the greater weight pressure, and drives the warm water upward, taking its place at the bottom of the vessel. This in turn becomes warmer, expands, and is driven upward by the colder water and so on, until the whole mass is heated to the boiling point or until the water on its way up and back gives up as much heat as it receives at the bottom. Similarly, when any other liquid or a gas is heated in this manner, the fluid itself travels as well as the heat. When a fluid receives heat at any place, travels with its heat, and gives it up to other bodies, those bodies are said to be heated by *convection*. Thus the air in the lower part of a room may receive heat by conduction from a stove or radiator, travel from the source, and give up heat to other air and various bodies in the room. This is a familiar example of heating by convection and of convection currents in air (Fig. 221).

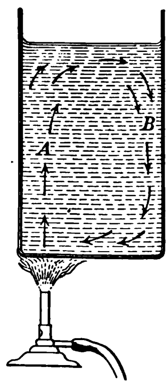


FIG. 220. — Circulation in vessel of liquid heated at the bottom.

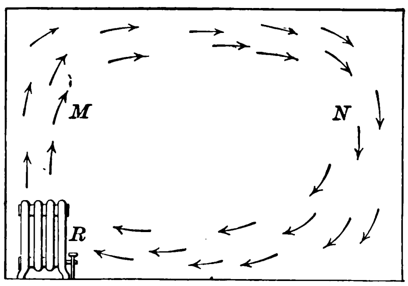


FIG. 221.—The circulation of air in a room heated by a stove or radiator R.

Since heat convection involves a circulation of the material, it is limited to liquids and gases.

An Illustration of Conduction and Convection. — There are two methods of transferring crude oil to the refinery: (1) It may be pumped through a line of pipes, or (2) a set of large tank cars may be filled at the oil well, which after they have traveled are emptied at the refinery. In the first case the oil travels but the containing vessel does not; in the second case both travel. The pipe line bears the same relation to the oil that a conducting body does to the heat it transmits. The tank car and oil sustain the same relation to each other as exists between the fluid and the heat transferred by the process known as convection of heat. Of course an important difference between the two lies in the fact that oil is matter and heat is energy.

143. **The Heating of Buildings.** — There are three distinct methods in common use for heating buildings in which convection plays an important part. These are commonly known as the hot air system, the steam system, and the hot water system. In the *hot air system*, the air to be admitted to a room after being heated by a furnace is driven through pipes into the room by the greater pressure of the colder and denser air outside, displacing as it enters the room an equal volume of air already there (Fig 222). In the *steam system*, water is boiled and

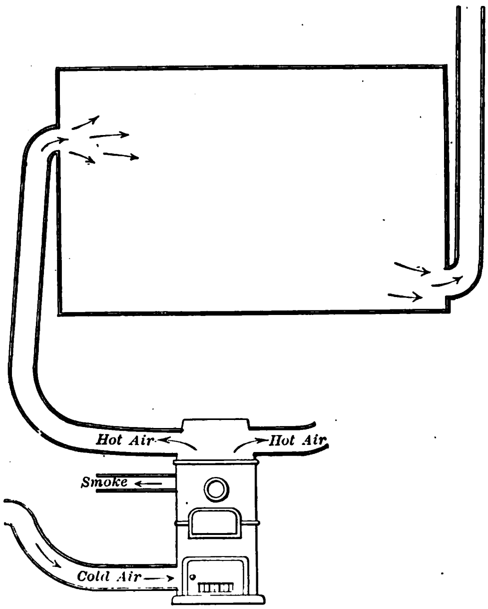


FIG. 222. — Hot air system of heating.

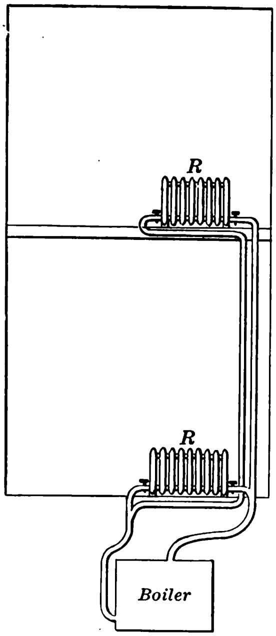


FIG 223.—A system of steam heating.

the steam is carried through a set of pipes into the radiators, good conductors with large capacity and surface. By its condensation in the radiators, the steam delivers up its heat of vaporization, 536 calories to the gram of steam. After it is liquefied, the water returns to the boiler, usually in another set of pipes, whereupon it goes through a repetition of the process already described (Fig. 223).

In the *hot water system*, a large pipe leads directly from the heater to the highest room to be heated, above which there is a small reservoir to keep the pipes constantly full and to provide for the expansion of the water. From this point, return pipes run to all the radiators and then back to the heater (Fig. 224). As the water in the boiler and in the direct pipe leading from it becomes heated, it expands (becomes less dense) and is then unable to counterbalance the pressure of the colder, denser water from the other pipes leading into the lower part of the heater. This unbalanced pressure establishes a circulation, the colder water continually pushing the hot water up in the direct pipe and down by way of the radiators, where by cooling it gives up heat to the radiators and the air in the room. A

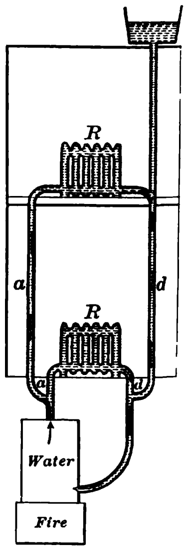


FIG. 224.—A system of hot water heating.

vater system requires more radiating surface to warm a room than a steam system requires, because it acts more y and because it lacks the heat of con- ıtion of steam.

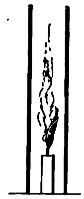


Fig. 225. — Warm air in chimney but no draft. No inlet.

the other hand, the hot water will flow even the fire is low, whereas with a steam system the boiling point of the water must be reached before any heat is transmitted to the radiators.

6.—No because no out-

144. The Circulation of Air in Ventilation. — The relation of heat to the motion of air in ventilation and in the production of winds can easily be shown by experiments with a lamp chimney and a candle. If a burning candle ıced within a chimney open at the top and closely to the table below, the candle will soon stop burning. This shows that the fresh cool air will not come in freely at the top (Fig. 225). If the chimney is now closed at the top and open at the bottom and the burning candle again admitted, it will again stop burning, showing that the warm air within prevents the cool fresh air from entering (Fig. 226). But if the burning candle is placed in the chimney when open at both top and bottom, it will burn indefinitely, the cool air entering below and driving out the warm, less dense air within (Fig. 227). If we place a partition in the tube (Fig. 228), the candle will burn even when the tube is closed at bottom. For now the cool air flows down on one side of the partition and drives the warm air up on the other.

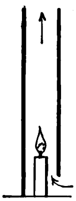
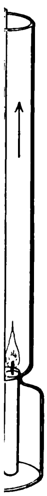


Fig. 227.— An inlet and an outlet give a draft.



:.—The r air up the ir.

In all these experiments the candle is used to warm the air in the chimney, and its place may be taken by a bar of hot iron suspended within. If we now suspend a piece of ice near the top of the chimney, we may reverse all the effects shown in the preceding cases, for cooling the air makes it denser than that without, and there is an excess of pressure downward within the chimney and outward below (Fig. 229). The motion of the air in each case can be readily shown by filling the chimney with smoke from burning touch paper, that is, filter paper that has been soaked in a solution of saltpeter and then dried.

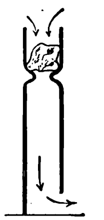


FIG. 229. — A down draft where the air is cooler.

These experiments show the conditions under which a natural draft or current of air is produced in the chimney of a house or in a room while being ventilated by windows and doors.

The conditions briefly stated are:

(1) There must be a difference in temperature to produce the difference of pressure which is responsible for the motion of the air.

(2) There must be an inlet and an outlet for the air (these are occasionally different parts of the same opening).

(3) When there is a difference in level between the inlet and the outlet the warmer air will move through the higher opening, or through the higher part of a single opening.

(4) The rate of flow through openings of a given size increases with the difference in temperature and the difference between the levels of the air at the openings.

It is not proposed to discuss the many problems involved in the satisfactory ventilation of a building, but when pumps or fans are not used, that is, when we depend entirely upon the "natural system," the principles above enunciated must be understood by one who would make intelligent use of the means at his command.

145. Winds. — In so far as they depend upon heating and cooling, winds are produced in much the same way as is a draft in a chimney. In a certain region, say the Mississippi Valley *M* (Fig. 230), there is a rise of temperature above that of the surrounding regions. As this warming takes place, the air in that locality, expanding upward, overflows above into the surrounding regions, *N* and *O*. As a consequence the barometric pressure at *M* decreases and at the same time the pressures at *O* and *N* increase. There will then be an excess of pressure toward *M* from both *O* and *N*, and the cooler air at *N* and *O* will move toward the point of less pressure, driving the warmer air upward at *M*. Nothing rises merely because it is hot, and the common statement that "warm air rises and cold air rushes in to take its place" conveys an erroneous impression. Warm air rises for a reason identical with that which causes a cork to rise when released under water. In brief, each rises because it is pushed up by a fluid which is denser than itself. Cooling is just as important a factor in the production of winds as is heating. For cooling increases the density and pressure of the atmosphere over a certain region, and the air in consequence flows out near the earth toward a region of higher temperature where the pressure is less.

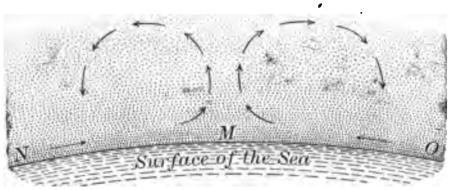


FIG. 230. — Showing how a circulation in the atmosphere originates.

QUESTIONS

1. In cold weather we keep ourselves warm by a woolen blanket, in summer we may keep a piece of ice cold by the same blanket. Explain, referring to transfer of heat.

2. What is the fallacy suggested by the common statement that there is "little warmth in linen"?

3. If water is heated by the application of the heat to the bottom of a vessel, how will the temperatures at different places in the water

compare (1) when the water is heated slowly, (2) when it is heated rapidly? Explain.

4. Explain why cold water put into a hot glass vessel or hot water put into a cold glass vessel usually breaks the vessel unless the glass is very thin.

5. When a room is heated by hot air, which is warmer, the air of the room or the furniture and other solid bodies? When the room is heated by steam or hot water radiators? When heated by an open grate fire?

146. Radiant Heat; the Medium. — When we stand before a bonfire or an open grate filled with glowing coals, we are conscious of receiving a great deal of heat on that side of the face toward the fire, while the other side may be cold. A piece of thin paper placed between the face and the fire immediately stops the coming of the heat. Plainly the heat energy comes *through* the air, but is *not transmitted by* it for the air is not appreciably warmed. Similarly, the sun may shine for a time through a clean window pane and warm the hand or a thermometer, without appreciably warming the air or the glass. Whenever heat is thus transmitted through a medium without warming it, the heat is said to be radiated. The real medium for so-called radiant heat is known as the *luminiferous ether* and it is neither the air nor the glass. The student is referred to the chapter on Light for a more comprehensive discussion of the ether and ether waves.

147. The Meaning of Radiation. — Any solid, liquid, or gas is said to radiate when it sends out energy in the form of ether waves. If these waves are of a suitable kind, they affect the eye, and are called light waves. When other waves fall upon some substance which will not transmit them, their energy is converted into heat. In this manner sunshine warms the hand. The waves are then said to be absorbed. Heat is said to be transmitted from one body to another by *radiation*, as from the sun to the earth, when in the process of transmission, the energy is not really heat as we commonly use the term, but becomes heat only when absorbed by some object. So-

called radiant heat is only one variety of a general kind of energy known as radiant energy.

148. The Radiometer. — The conversion of radiant energy into heat and mechanical motion is beautifully shown by a simple little instrument, devised by Sir William Crookes, and called by him a radiometer (Fig. 231). It consists of a bulb from which the air is exhausted to less than $\frac{1}{100}$ of the ordinary atmospheric pressure. Within the bulb there is suspended on a needle point a light aluminum wheel which has a set of four or more vanes on its circumference. Each of the metallic vanes is polished on one side and blackened on the other, the blackened sides being all directed the same way around the circumference of the wheel. If the instrument is held in sunshine or in the radiations from a flamé, the blackened surfaces will all absorb more energy, hence become more heated than the polished sides.

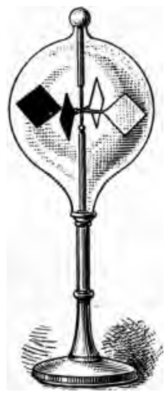


Fig. 231.—Crookes's radiometer.

On this account there is a greater pressure between the heated air and the black sides of the vanes, and consequently there is a moving of the vanes away from the air, thus producing a rotation of the wheel. Since an increase in the intensity of the radiations will produce a greater speed of rotation, the instrument is helpful in studying radiant energy.

149. Prevost's Theory of Exchanges. — If a number of objects, none of which are generating heat, are placed in the same room, all finally acquire practically the same temperature even when there is no conduction nor convection. A colder body brought in will become warmer, and those already there will become colder. If a warmer body is introduced it loses and all the others gain heat.

These and other facts have led to the following conclusions:

(1) that every body is always giving off heat through the ether or radiating heat at a rate depending upon its temperature; (2) that the temperature of a body rises when it receives more heat by absorption than it loses by radiation; and (3) that the temperature of a body falls when it loses more heat by radiation than it gains by absorption. If there is no change in the temperature of a body, the heat lost by radiation and the amount gained by absorption are equal. Since radiation takes place at the surface, the cooling of a body by radiation is greatly facilitated by increasing the external surface. This is applied in the construction of radiators in heating plants and in the cooling arrangement of automobiles.

150. Laws of Heat Radiations. — *Heat radiations are reflected, refracted, undergo changes of intensity, and are transmitted* according to the same laws as are the radiations which produce the sensation of sight known as light radiations. The laws governing these different processes find more important applications in connection with light radiations and they are therefore discussed in the chapter on Light.

151. Absorption, Emission, and Reflection of Heat Radiations. — Lampblack absorbs practically all the radiations which fall upon it and reflects none. Other black substances are also good absorbers and poor reflectors.

Polished metals reflect a great deal, and absorb correspondingly less, of the heat radiations which strike them.

For substances which do not transmit the radiations, the absorbing power and the reflecting power are jointly equal to the absorbing power of pure black (lampblack).

The emissive or radiating power of a substance is equal to its absorbing power.

Generally speaking, black, unpolished substances are the best radiators and absorbers, and the poorest reflectors, while white polished bodies are the poorest radiators and absorbers but the best reflectors of radiant heat.

152. The Radiant Heat of the Sun in its Relation to the Atmosphere. — Pure, dry air is nearly perfectly transparent to radiant energy, hence the sunshine reaches the solid and liquid portions of the earth without heating the air to any considerable extent. On the other hand, at night the cooling of the earth occurs chiefly on account of the radiating of heat through the transparent air by the same solids or liquids which absorb the radiations by day. From this it is evident, that on a clear day, the atmosphere is heated and cooled chiefly by its contact with the land and the sea and by the convection currents thus produced. Water vapor, clouds, dust, and smoke absorb a very considerable part of the radiant energy on its way through the air, hence the atmosphere is heated to a much greater extent when they are present, and the land and sea beneath to a correspondingly less amount. For this reason, on the dry, clear air of a winter day, there is such a sharp contrast between the temperature in the sunshine and that in the shade, or between the temperature of the day and the night. In the vapor-laden, hazy days of summer, on account of the blanket of water vapor and mist, there is less difference between the temperatures of sunshine and shadow, and between those of day and night.

Heat and Work

153. Historical Sketch of the Doctrine of the Conservation of Energy. — Until comparatively recent times heat was believed to be a kind of substance having no weight. The idea that heat was due to a kind of motion or "brisk agitation" was suggested by Lord Bacon. In 1798, Sir Humphry Davy melted two pieces of ice by rubbing them together, and in 1799, Benjamin Thompson (an American, afterward Count Rumford) produced sufficient heat by friction to raise about 27 lb. of water from freezing to the boiling point. These were the first experiments which served to furnish information from which the true nature

of heat might have been inferred. It was not until 1843 that Joule of England first satisfactorily demonstrated the relation between heat and mechanical work, and thus laid one of the foundation stones upon which rests the principle of the *conservation of energy.*

154. **The Mechanical Equivalent of Heat.** — It was shown early in our discussion of the nature and source of heat that mechanical motion can be converted into heat, and that heat can do mechanical work. The exact relation between heat and work was first established by the elaborate experiments of Joule referred to in the last section. He arranged large bodies in such a way that their gradual descent would move the paddles in a vessel of water. From the rise in temperature of the water and its mass, he determined (1) the quantity of heat generated by the stirring. By knowing the weight of the bodies and the vertical distance that they descended, he determined (2) the quantity of work in foot pounds. Joule announced, as his final result, that 772 ft. lb. of work is the equivalent of 1 B.T.U., that is, the heat required to warm 1 lb. of water through 1° F. More recent work and more accurate methods of measurements, have given 777 ft. lb. as the mechanical energy equivalent to 1 B.T.U. Expressed in the C.G.S. units, 41,900,000 ergs is the mechanical equivalent of 1 gram calorie.

155. **The Work done upon a Gas and the Work done by a Gas.** — When a gas is compressed, work is done upon it and its temperature rises. The heat which is produced is the equivalent of the mechanical work which is done. If the gas is now allowed to expand and move a piston, or expand by projecting its molecules out against the air, the gas is cooled. In this case, the heat which disappears from the gas has its equivalent in the mechanical work which it does. Various machines or heat engines have been devised for the purpose of converting into mechanical motion the heat energy of a compressed gas, or the heat energy of a gas generated under pressure.

Though their forms are numerous and in most cases their structure and working very complicated, for our purpose, we may arrange these *heat engines* under three types: (1) The *compressed air engine,* or a type in which work is done upon a quantity of air at one place, to be given up subsequently by the expansion and cooling of the air at another place. (2) Those *engines which use the expansion energy of some highly heated gas or vapor,* which is generated, as is steam, in a boiler and then conveyed to a movable piston or revolving disk, on which it does its work. (3) Those engines which introduce into a cylinder an *explosive mixture of gases,* for example, gasoline vapor and air, and then suddenly heat the gases by a chemical process called an explosion.

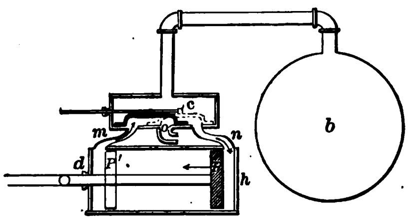


FIG. 232. — Showing the essential features of the slide valve and the working of the piston in a common locomotive or reciprocating engine.

156. The Steam Engine. — Heat engines which depend on steam as the working material may be considered under two classes:

1. Those which convert the heat energy of the steam into the to and fro motion of a piston in a cylinder. A familiar example of this kind of engine, known as the *reciprocating engine,* is the railroad locomotive. The steam is carried from the boiler *b* (Fig. 232) into a box *c* known as the valve chest. Attached to this valve chest there are two tubes *m* and *n* leading to the ends of the cylinder, and a third, *o,* called the exhaust, which is in communication with the atmosphere, or with a condenser. Over these openings is placed a valve which consists of a block of metal having a cavity underneath of such a size that when the block is pushed to one end *m* of the valve chest, the one end *h* of the cylinder is in communication with the steam in the steam chest, and the other end of the cylinder, *d,* by way of the cavity, is in communication with the exhaust. When the valve

is in the position shown in the cut, steam from the boiler is admitted through *n* between the piston and the cylinder head *h* and drives the piston toward *d*. At the same time any steam remaining from the last stroke between the piston and the cylinder head *d* may escape through tube *m* and the exhaust *o*. The sliding valve is so attached to the rotating part of the engine that by the time the piston reaches *d*, the valve has been pulled to the other end of the valve chest, as shown by the dotted line, putting *n* in communication with the cylinder and *m* with the exhaust. The entrance and exit of the steam and the motion of the piston and valve are now the reverse of those just given.

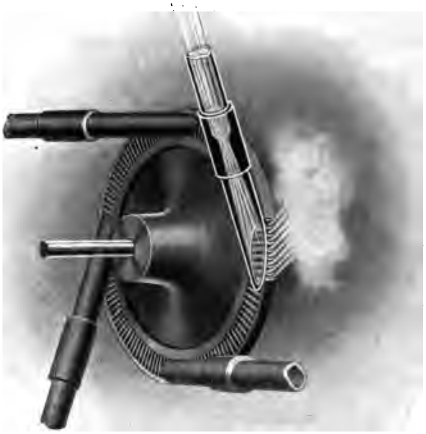


FIG. 233. — Illustrating the principle of the turbine engine.

2. Another class of steam engine, known as *the turbine*, is one in which the steam gives up its heat energy in first imparting velocity to its own particles or molecules. This rapidly traveling mass strikes against the blades of a wheel, or set of wheels, in such a way that the wheel is set in rotation. The gain in energy of the wheel is due to the loss of velocity of the steam particles. The principle is well shown by letting the compressed air from a bicycle tire set in motion a pin wheel held close to the open valve. The principle of a simple form of rotary or turbine engine is shown in Figure 233. The steam expanding after it escapes from a check valve acquires a high velocity in the nozzles, and striking against the blades in the wheel set it into a rapid rotation. Better results are se-

cured by letting the steam expand in several stages, and thus by taking some of the energy out of it after each expansion, prevent it from ever reaching such a high velocity. Figure 234 shows a form of turbine in which this is accomplished.

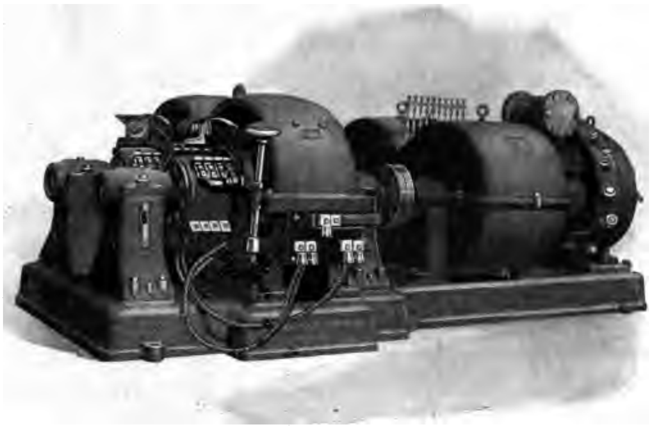


FIG. 234. — Compound turbine engine coupled directly to a dynamo.

QUESTIONS AND PROBLEMS

1. How many ergs are equivalent to 1 gram calorie? How many ergs are equivalent to 1 gram centimeter of work in the latitude of New York? How many gram centimeters are equivalent to 1 gram calorie? How many joules are equivalent to 1 gram calorie?

2. If all the kinetic energy of a falling body were converted into heat when it strikes, through what vertical distance must 1 gm. of water fall to generate enough heat to raise its temperature 1° C.? Through what distance must 1 gm. of copper fall to raise its temperature 5° C.?

3. What effect does expansion have upon the temperature of a gas? What becomes of the heat?

4. If the average pressure in a steam engine cylinder is 80 lb. per square inch and the area of the contact surface of the piston is 250 sq. in., how much work does the steam do in moving the piston 18 in.? What effect does the doing of this work have upon the steam if it is not in communication with the boiler?

5. What is the meaning of the expression "The efficiency of a steam engine is 10 per cent"?

6. From what height must a mass of ice fall in order to generate

enough heat to melt itself if all its kinetic energy produced by the fall is converted into heat by the impact?

7. If the burning of 1 gm. of coal generates 7800 gram calories and the efficiency of an engine is 10 per cent. find how much coal is consumed by a 10 kilowatt engine in 1 hr. How much is consumed by a 20 horse power engine in 2 hr.?

XI. WAVES AND WAVE MOTIONS

157. Kinds of Vibrations or Oscillations. — Probably the most easily appreciated case of vibratory motion is that furnished by a simple pendulum already discussed (section 95). Similar to this is the vibration of a rod of wood or metal when fastened at one end, as shown in Figure 235. As previously shown, the pendulum vibrates on account of its weight or gravity, but the rod vibrates on account of its elasticity.

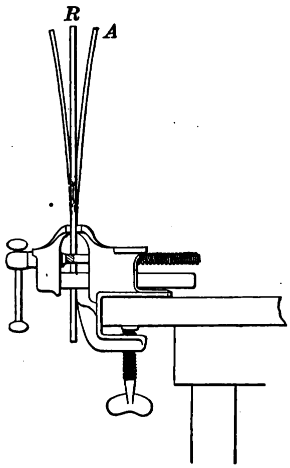


FIG. 235. — Showing the vibration of a rod fixed at one end.

In either case, the distance *RA* (Fig. 235) is the *amplitude* and the motion from an extreme point *A* to another extreme point *B* and back again to the first point, is called *a complete vibration.* The *time* required to execute a complete vibration is called the *period of vibration.* A long coil of elastic wire fastened at both ends, as shown in Figure 236, when displaced

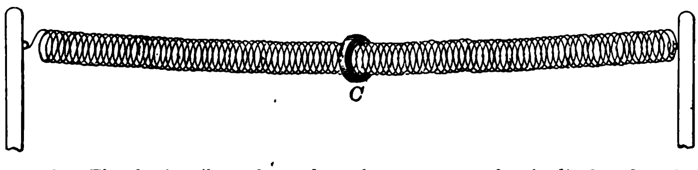


FIG. 236. — The elastic coil may be made to show transverse longitudinal, and torsional vibrations.

vertically from its neutral position and released, will vibrate, each particle of the coil moving in practically a straight line.

This is an example of a *transverse* vibration, that is, a vibration at right angles to the length of the vibrating body. If a cork C, fastened to the middle of the coil, is displaced toward either end of the coil and then released, the cork and particles of the wire to which it is attached will vibrate in the direction of the length of the coil, showing what is known as a *longitudinal* vibration. After the coil again comes to rest, if the wire at or near the coil is seized, twisted, and then released, the cork will rotate, for a time in one direction, then in the opposite direction, and so on, vibrating like the large balance wheel in a watch. This kind of motion is called *torsional* vibration. Any two or all three of these kinds of vibrations can be produced at the same time by setting up jointly the conditions which produce each singly.

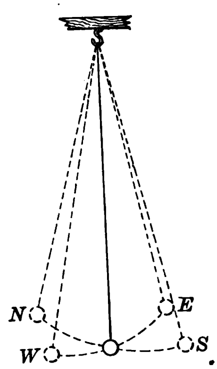


FIG. 237.—Showing vibration in two planes.

If a simple pendulum is suspended from a point and is displaced toward the south, it will vibrate in a north and south plane. If it is next displaced toward the east, it will vibrate in an east and west plane (Fig. 237). But, if we displace it toward the south and then give it a slight thrust eastward, the pendulum bob will have a motion which is the resultant of the two former motions and, if the thrust is properly gauged, it will move around a circle (Fig. 238). To a distant observer, whose eye is on the level of the pendulum bob and stationed north or south of it, the bob will seem to vibrate on a straight line east and west. To another person similarly located east or west of the bob, it will seem to vibrate along a straight

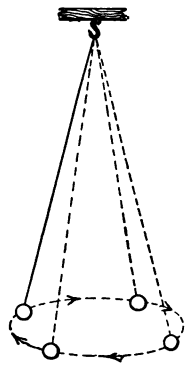


FIG. 238.—A conical pendulum. When viewed from a distance on the level of the pendulum bob shows simple harmonic motion.

line north and south. Each observer sees only one of the two component vibrations, and each apparent vibration is approximately an example of what is known as a *simple harmonic motion,* the kind of motion that sounding bodies have.

Geometrically, a simple harmonic motion is readily shown as follows:

On the circumference of a circle, beginning at the lowest point, place marks say 30° apart around the entire circle (Fig. 239). Draw a horizontal line ag a short distance below the circle. From each of the points marked, let fall a perpendicular upon the horizontal line. If a body were to vibrate along this straight line in such a manner as to require the same time to go from each point to the adjacent point, the body would have a *simple harmonic motion.*

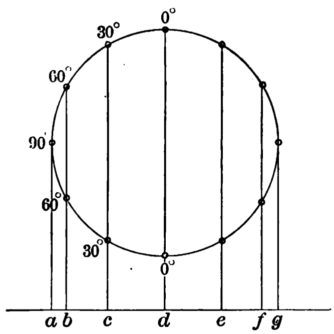


FIG. 239.

Any point on a wheel, rotating with a constant velocity, when viewed from a distant point in the plane of the wheel, furnishes another approximate example of a simple harmonic motion.

158. **The Transmission of Vibrations; Waves.** — When we drop a stone into smooth water, the blow of the stone throws the water into vibrations, but the particles which are struck quickly pass their energy to their neighbors and they in turn to the next and so on, the vibratory motion traveling away from the point of disturbance along the surface of the water, in all directions, in the form of circular waves.

If we strike one end of the coil of wire (Fig. 236), and thus give it a quick transverse vibration, we see that this vibratory motion is transmitted along the coil. Or if we grasp the coil at two places near one end and compress or stretch the coil between

the hands so as to produce, when released, a longitudinal vibration, the motion of the coil and cork C tells us that this vibration has likewise been transmitted. In both cases, we say that waves have traveled along the coil.

In general, when vibratory motions are being transmitted by the distortion or compression of any material, during the transmission the material assumes certain forms or conditions known as *waves.* A succession of waves from a common origin, such as those which follow each other when a stone strikes the surface of water, is called a *train of waves.*

159. **Surface Waves; Wave Length.** — The simplest waves are those on the surface of water, which, when originating at a single point, appear as constantly enlarging circles with a common center. Generally speaking, the particles of water rise and fall, vibrating transversely, whereas the waves move horizontally in all directions from the center of disturbance.

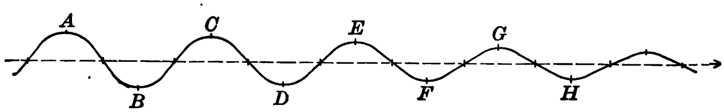


FIG. 240. — A vertical section through a train of water waves, showing a constant wave length and a decreasing amplitude.

Figure 240 shows a vertical section, through a train of water waves, produced by a disturbance near A. The arrow represents the direction in which the waves are traveling. The water in the front part of each wave between AB, CD, and EF, etc., is rising, whereas the water on the rear of each wave between BC, DE, etc., is falling. The crest, or highest point, of each wave form, but not the water there, is moving horizontally toward the point where a trough now is, hence one half of a vibration period later, the points A, C, E, G, will be troughs, and B, D, F, H will then be crests. At the end of a period the water particles will have returned to the position shown in Figure 240, but the particular wave which is at A

will then be at C, having advanced the distance AC in the period or the time of one complete vibration. The distance AC (Fig. 240) or mo (Fig. 241) is called the *wave length.* The wave length may then be stated as the distance, measured in the direction the wave is moving, from any point in a wave to that point in the next wave which is in the same state of motion. Plainly, *the wave length is also the distance the wave advances in the time of one vibration.*

FIG. 241. — The wave length is here one half as great as that shown in Figure 240.

160. Kinds of Waves. Wave Fronts. — Waves may be transmitted (1) as they are by the coil, approximately along straight lines; (2) through a medium in all directions in one plane, as they are in the case of the water; or (3) through a medium in all directions, as they are in the air and ether. This gives us three varieties, — *linear, surface,* and *spherical* waves, — the last of which are the most important in physics. As waves pass out from a center of disturbance, a line or surface can be described or imagined which marks at any instant all the points which the vibratory motion or disturbance has then reached. These lines or surfaces are known as *wave fronts.* Thus the wave front of each of the simple water waves already discussed is approximately a *circle.*

The wave fronts produced in air by a small vibrating bell are *approximately spherical surfaces,* or spherical shells, as are also the wave fronts produced in the ether by an arc light or a small candle.

161. The Velocity of Waves; the Relation of Velocity to Wave Length and Period. — The distance a wave or a wave front advances in a unit of time expresses the *velocity of the wave.* If a substance had no elasticity it could not transmit vibrations, hence the speed with which the particles of a sub-

stance pass on their vibratory motion to their neighbors is increased by an increase in the elasticity of the substance. On the other hand, the more dense a substance is, the more mass there is to be started and stopped at each vibration, hence if the elasticity remains constant, the more slowly the vibratory motion travels. Newton discovered that the relation between the velocity of a compressional wave and the elasticity and density of the medium may be expressed as follows:

$$\text{The velocity of a wave varies as } \frac{\sqrt{\text{elasticity}}}{\sqrt{\text{density}}}.$$

Consequently in a medium such as air, the velocity of the spherical sound waves is increased by any increase of the elasticity of the air, whereas an increase in the density of the air decreases the velocity of the waves.

Since the velocity of a wave is the distance the wave front advances in a unit of time, and the wave length is the distance it advances in the period, it follows that the same relation exists between the velocity of the wave and the wave length, as exists between the unit of time and the period or time of one vibration, therefore:

$$\frac{\text{velocity}}{\text{wave length}} = \frac{\text{unit of time}}{\text{period}}.$$

Any three of these four quantities being known, we can compute the fourth. For example, if the velocity of a sound wave in air is 1100 ft. per second, and the period is .02 of a second, we may find the wave length thus:

$$\frac{1100 \text{ ft.}}{\text{w. l.}} = \frac{1 \text{ sec.}}{.02 \text{ sec.}} = \frac{50}{1}$$

$$50 \text{ w. l.} = 1100 \text{ ft.}$$

$$\text{w. l.} = 22 \text{ ft.}$$

XII. SOUND

162. The Two Meanings of the Term "Sound." — The term *sound* is commonly applied to any *sensation* derived through the organ of hearing, the ear. In this sense of the term sound does not exist for a perfectly deaf person. Since the hearing organ is defective, no sensations of this kind are produced. The word sound is also used, in a general way, to indicate the *external physical conditions* which precede the production of the sensations, such as the vibration of the source and of the transmitting medium. In this sense sound exists independent of the hearer. In physics this latter meaning of the term is the one chiefly used.

163. The Origin of Sound Waves. — If we touch with the fingers a sounding tuning fork, piano wire, or a bell, we can readily perceive that they are vibrating (Fig. 242). If a glass tube (Fig. 243), containing cork dust, is closed at one end and a whistle tightly inserted in the other, the motion of the powder shows that the air within the tube vibrates when the whistle is blown. A sound is likewise produced by a stream falling into a body of water. These facts show that *sound waves originate in a vibrating body, which may be a solid, a liquid, or a gas.*

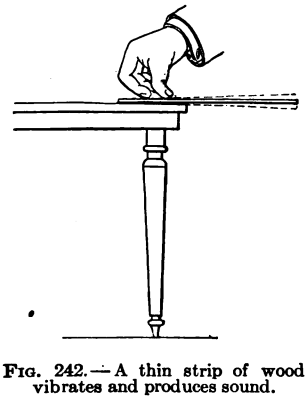


Fig. 242.— A thin strip of wood vibrates and produces sound.

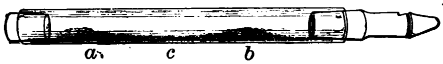


Fig. 243.—The vibration of the air in the tube is shown by the motion of the dust.

164. The Transmission of Sound. — The vibrations of the body, originating the sound, are communicated to some material in contact with this vibrating body, and by this material they are transmitted in the form of waves. Any material which transmits a sound wave is called the *medium*. This medium may be a gas, a liquid, or a solid, but the sounds we hear are most commonly transmitted by the atmosphere.

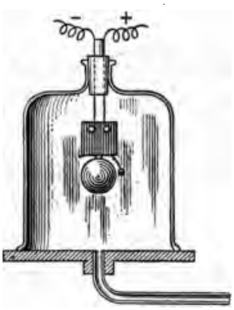


FIG. 244.

The fact that a vibrating bell becomes almost inaudible when suspended in a vessel from which the air is being exhausted convinces us that sound waves could not be transmitted through a perfect vacuum, a space without ordinary matter (Fig. 244).

165. Shape of Sound Waves; Direction of Motion of Particles. — When a succession or train of sound waves is produced in the quiet air, each wave front is an approximately spherical surface or shell which grows larger as the wave advances. The air particles move back and forth along the radii of these spheres, executing what is called a *longitudinal vibration*. The result of this motion of the particles is the production of certain alternate condensations and rarefactions in the air, as shown in Figures 245

FIG. 245. — A section through a wave train, showing at a given instant the alternate condensations and rarefactions in the air which travel outward from the center with the speed of sound.

and 246, the first of which represents either a horizontal or vertical section through a wave train and its source. If the wind is blowing, the advancing waves will become distorted, for the speed of the wind will hinder the advancement of the

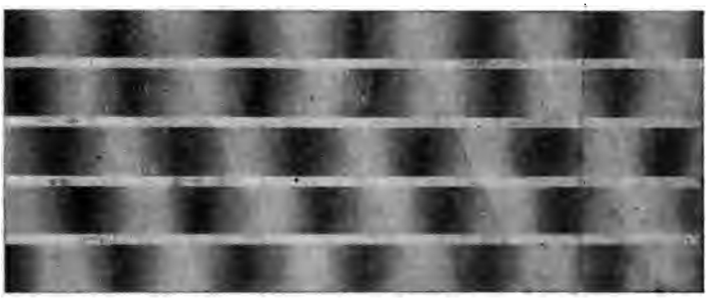


FIG. 246 shows the progress of a part of a train of compressional or sound waves. Each train is ¼ period and ¼ wave length in advance of the one above it. Each wave is traveling toward the right, and its energy decreases as it advances.

wave front on one side of the source and assist it on the other. Any lack of uniformity of the air or the presence of other bodies, such as trees, houses, hills, etc., also produces changes in the shape of the waves.

166. Velocity of Sound. — A person observing the blows of a hammer when only a few feet away will hear the blow at practically the same time that he sees the hammer strike. If the distance between the observer and the hammer is several hundred feet, there is an easily observed interval between the seeing and the hearing of the blow. Similarly, when a steam whistle is at a great distance from the hearer, the issue of the steam may be seen some time before the sound is heard. We are accustomed to decide roughly whether a lightning flash is distant or near by the time the sound lags behind the light. All these facts prove that it takes a considerable time to transmit the sound waves. Accurate experimenting has determined that the velocity of sound in air, at the freezing point, is about 1090 ft. (332 m.) per second.

It has been stated that the velocity of a wave within a medium depends upon the elasticity and density of the medium transmitting it.

$$\text{Velocity varies as } \frac{\sqrt{\text{elasticity}}}{\sqrt{\text{density}}}.$$

The atmosphere is a mixture of gases. Any change in the relative proportions of these gases, for example, the adding or withdrawing of water vapor, changes the density of the air, hence changes the velocity of sound. When a gas is heated it will either expand or increase its pressure, and either or both of these effects will increase the velocity of the waves. (See Boyle's and Charles's laws, sections 39 and 118.) For when a gas expands under a constant pressure, its density becomes less, hence the velocity of the wave becomes greater. If, however, air or any other gas is heated and not allowed to expand, the increased pressure indicates an increased elasticity and on this account the velocity of sound is increased. The velocity of sound in the air increases approximately 1 ft. per second for each 1° F. rise in temperature. Hence, at 72° F. or 40° above the freezing point, the velocity is about $1090 + 40 = 1130$ ft. per second.

If we observe a workman at a distance of several thousand feet driving a spike into a railroad tie, we can hear two sounds for each blow, one wave being transmitted by the air, the other by the iron. The wave that comes through the iron arrives first. Generally speaking, the velocity of sound in liquids and solids is much greater than in air. Though they are hundreds and some of them even thousands of times as dense as air, the high degree of elasticity of solids and liquids more than compensates for their large density. The relative velocities of sound in air, water, and iron are about 1:4:16, respectively. The accompanying table gives the velocity of sound in some of the most common substances:

SUB.	TEMP. C.	VELOC. IN FT. PER SEC.	VELOC. IN METERS PER SEC.
Air	0°	1090	332.3
Hydrogen	0°	4221	1286.4
Illumin. Gas	0	1609	490.4
Water	4°	4591	1399.
Oak		12620	3850.
Iron	20°	16820	5130.

167. Reflection of Sound Waves; The Echo. — When a wave in the coil of wire (Fig. 236) comes to the end of the coil, there are two things either or both of which may happen: (1) the vibratory motion may be taken up by the new medium, which begins where the coil ends; or (2) the wave may be returned along the coil. An empty box attached to the end of the coil, because it is well disposed to take up vibratory motion, tells us by the sound it emits that a part at least of the wave energy has been admitted. Similarly, a sound wave, traveling from its source in all directions through the air, frequently comes to places where the air suddenly ends, for example, at a wall or a tree. Each new medium admits a part and rejects the remainder of the energy of the wave. The rejected portion called the reflected wave will move away from the surface of the body according to a *law of reflection*, which can be demonstrated roughly by throwing a rubber ball against a plane surface in different directions, as represented in Figure 247. If the ball be thrown along the line (1) it will be reflected along the line (2), but when thrown along the line (3) it will rebound along the line (4), though the weight of the ball interferes

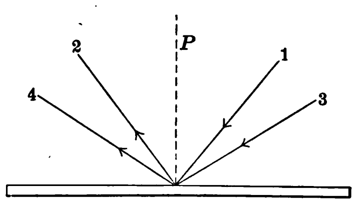


FIG. 247. — Showing the law of reflection of a wave.

somewhat with the accuracy of the results. A much more exact demonstration of the principles of wave reflection can be made with light waves as shown in section 194.

In general, the direction of a reflected wave can be found as follows: Select any point A, in the wave front (Fig. 248), and trace it to and from the surface of reflection so that its path going from the surface will make the same angle with the perpendicular to the surface as the path of approach makes with it. Thus angle APO = angle BPO. When surfaces are rough and irregular, as they frequently are where the reflection of sound is involved, the perpendiculars are very differently directed at different points, thus giving quite a variety of directions to the reflected waves. But a wall or cliff may be sufficiently regular to give a fairly definite reflection.

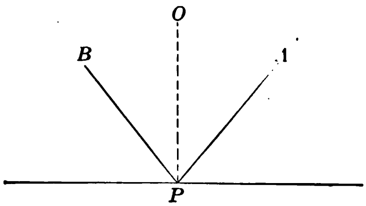


FIG. 248.

The Echo. — The shortest line between a source of sound and the hearer of it is plainly the straight line connecting them. To reach the hearer a reflected wave travels a longer distance than a direct wave and consequently arrives later. This is true whether the hearer and speaker are the same person or not. Whenever the reflected sound wave arrives a sufficiently long time behind the direct wave to be distinguishable from it, two sounds are produced from the same cause. Under these conditions the reflected sound is called *an echo*. Since we are unable to distinguish sounds unless they are at least $\frac{1}{10}$ of a second apart, the reflected sound must travel about 110 ft. farther than the direct, in order to be $\frac{1}{10}$ of a second behind it; hence, to hear the echo of his own voice, a speaker could not be *nearer* than about 50 or 55 ft. from the reflecting surface. For this reason echoes, properly speaking, are not noticed in small rooms though the reflection of the sound waves always occurs.

When one is in an empty room or in a long narrow hall or tunnel, a simple short tone is followed by a prolongation of the sound called *reverberation*. This is the result of the reflection of the sound waves back and forth from surface to surface until the energy is finally all absorbed or changed to heat. Carpets, furniture, or an audience, prevent to a great extent this successive reflection or reverberation. The total absence of reverberation, because the tones then cease so quickly, makes music seem dead. In a speaking tube and the ear trumpet we use this multiple reflection to prevent the spread of the sound waves and thus preserve their intensity.

Thus far we have spoken of the portion of a sound wave which strikes a new medium and does not enter it. The portion which enters is partly transmitted and partly absorbed. Curtains, carpets, soft rubber, etc., are poor reflectors and poor transmitters of sound waves. Material used to "deaden" the walls and floors must be such as readily absorb the sound energy.

168. Forced Vibrations. — If a large and a small ball are suspended with strings of slightly different length, the two pendulums thus constructed will have different rates of vibration, the small one having the shorter period (Fig. 249). If we fasten the ball x to the cord of y, we now find that they both vibrate in practically the same period as y does when alone. Since pendulum x has been compelled to vibrate in the same period as y, the vibration of x is now called a *forced vibration*, that is, x is not vibrating in its own natural period. In general whenever any body is compelled to vibrate in any period different from its own natural period, the vibrations are said to be forced. A tuning fork when put into vibration and then placed upright on a table, sets the table top into forced vibrations.

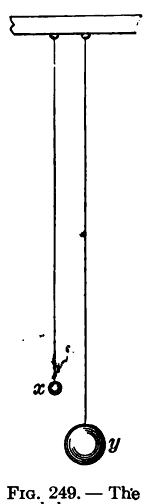


Fig. 249. — The pendulum x can be forced to vibrate in the natural period of y.

Similarly, a sounding board of a piano or other stringed instrument is thrown into forced vibrations, which have the same period as that of the vibrating string. These forced vibrations increase the intensity of the sound waves emitted, but the fork or string, when producing forced vibrations, gives out its energy more rapidly; hence it cannot vibrate for so long a time.

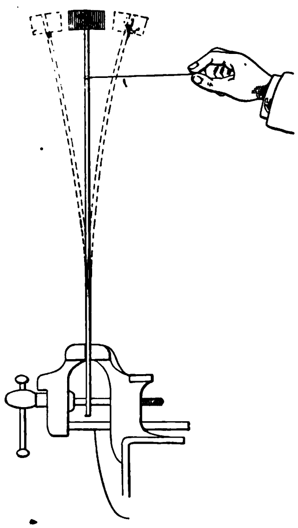


FIG. 250. — The rod with its heavy load can be set into vibrations by a frail thread if the pulls are timed to suit the natural period of the rod.

169. Sympathetic Vibrations; Resonance. — A strip of wood fastened at one end (Fig. 250) can be thrown into vibrations of large amplitude by means of a very slender thread, provided the successive pulls on the thread are timed according to the natural period of the rod; that is, if the hand of the experimenter vibrates in the same period as the natural period of the rod. A vibration produced by an agreement between the natural period of one body and that of another is called a *sympathetic vibration*. For example: A tuning fork of a given period will set into sympathetic vibration another fork of identical period, even when they are separated by several feet of air (Fig. 251). The first fork sends out vibrations of its own period, and each successive wave strikes the second fork at just the right time to add its motion to that previously given, just as properly timed pushes and pulls, though each is feeble, will, if continued, put a large swing into vibration.

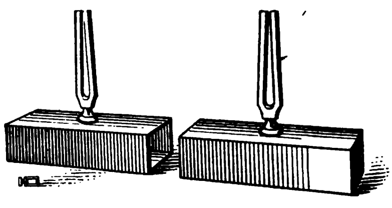


FIG. 251. — Sympathetic tuning forks.

If a vibrating tuning fork is held in the hand near the mouth of an empty bottle of suitable size and the mouth of the bottle gradually closed with a glass plate, we finally hear a loud sound apparently issuing from the jar (Fig. 252). When the natural period of a body of air is the same as the period of the source, the sound, produced by the sympathetic vibration of the air, is called *resonance.*

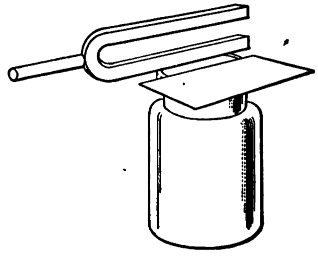


FIG. 252. — Resonance: the sympathetic vibration of the air in the jar.

Sounds produced by the human vocal chords alone are very feeble, the "volume" of the tone being due largely to the resonance of the mouth cavity. Likewise, tuning forks produce the strongest tones when mounted on boxes, the air space of which is so adjusted to each fork that resonance is produced.

170. The Intensity of Sound; Loudness. — The *intensity* or *energy per unit surface* of a sound wave depends upon the amount of energy given to it at the source, and the changes which occur during its transmission. The *loudness* of a sound involves sensation and depends upon both the intensity of the wave and the condition of the hearing organ, though for any one person relative loudness may be used to measure roughly the relative intensities of sounds.

The intensity of a sound wave at its source varies (1) directly as the square of the amplitude of the vibrating body, (2) directly as the extent of surface of the vibrating body, and (3) directly as the density of the medium in contact with the vibrating body. Since a wave front, in the open air, is approximately spherical, the energy of each advancing wave is being distributed over the constantly increasing number of surface particles of this enlarging sphere. As the wave travels, its intensity, or amount of energy, per unit surface will

therefore become smaller at the same rate that the surface of the sphere becomes larger. But the area of a sphere increases as the square of the radius, or distance from its center, hence, *the intensity at any point in a given sound wave varies inversely as the square of the distance from the source.* This, of course, applies only to the direct wave. The *total intensity*, in most cases, is greatly increased by reflections from walls, houses, trees, and other bodies. The upper portions of waves moving with the wind travel faster above than the parts near the ground where the speed of the wind is less, hence, the waves are diverted downward and thus they make the sound louder than it would otherwise be at that distance from the source. Those waves traveling against the wind are oppositely affected. In general, any conditions which affect the uniformity of the air, such as rapid heating or cooling, also affect the intensity of the sound and the distance at which a given sound can be heard.

171. **Interference of Sound Waves.** — When one wave meets another in such a manner that both tend to produce simultaneously a condensation or a rarefaction at the same place, the two effects will be added; but if they so meet that one endeavors to produce a condensation just where the other is trying to produce a rarefaction, the resultant motion will be the difference between the two, and the waves are said to *interfere.* When the two waves meeting thus have equal amplitude, the interference is complete, and no sound is produced at that place. If we slowly rotate a tuning fork while it is producing resonance at the mouth of the bottle (Fig. 252), a position will be found in which the waves entering the bottle from the two prongs interfere, and no resonance is produced. When the two prongs are equally near the opening, or when one completely screens the waves of the other from the jar, there is no interference.

172. **The Pitch of Sounds.** — Beginning at one end of the keyboard of a piano and striking the keys in succession, we are conscious of a difference in the character of the tones produced.

We may express this difference in the character of the sensations by saying some notes are low, and others are high or shrill notes. Briefly we say the notes differ in pitch.

If we draw the edge of a calling card quickly along the teeth of a comb or hold it against the cogs of a rapidly revolving cog wheel, we can show that the pitch of a sound varies with the number of vibrations per unit of time, that is, with *the vibration frequency.* A more exact method of showing the relation of pitch to vibration frequency is shown in Figure 253. A disk of metal or stiff cardboard, containing one or more circular rows of holes, is revolved rapidly, and a current of air is sent through a tube, the open end of which is held near to one of the rows of holes. The puffs of air through the holes as they come opposite to the tube throw the surrounding air into vibration, thus producing a sound. The number of puffs per second is the same as the number of holes passing the end of the tube per second, hence we have here the basis of a method of computing the vibration frequency of a given tone. An instrument based on this principle, sometimes having a mechanism for counting the revolutions, is called a *siren.*

FIG. 253. — Metal siren.

Just as the long waves on water have shorter waves upon them, so the waves given off by most sounding bodies are generally a mixture of waves of different frequency. Thus a violin string may vibrate as a whole or in parts (see sec. 181), giving rise at the same time to several sounds of different pitch or vibration frequency. The pitch of the lowest or gravest component, produced by the string vibrating as a whole, is called the *fundamental.*

173. Relation of Vibration Frequency to Wave Length and Velocity. — Since sounds of all frequencies or pitch have the same velocity, it follows that the greater the number of waves

sent out by the vibrating body in a second, the less distance each wave will be in advance of the next, that is, the shorter will be the wave length. Hence, the wave length may always be found by dividing the velocity of the sound by the number expressing the frequency, or

$$\text{wave length} = \frac{\text{velocity}}{\text{number of vibrations}}$$

$$\text{wave length in feet} = \frac{\text{velocity in feet per second}}{\text{number of vibrations per second}}.$$

For example, if a certain tone has 256 vibrations per second, the wave length when the velocity is 1090 ft. per sec. is $1090 \div 256 = 4.+$ ft.

174. **Doppler's Principle.** — If the source of a sound is moving toward or from the observer, the pitch of the tone is affected. For example, the whistle of an engine or the bell of a bicycle is decidedly higher in pitch as the source approaches than it is after it has passed the observer. This is due to the fact that each successive wave starts from a new point, as much nearer or farther from the observer as the source moves in the time of one vibration. This results in an increase or decrease in the number of vibrations which reach the observer in one second compared to what would reach him if the source were not changing its position. Consequently the pitch is raised when the source and hearer are approaching, and lowered when they are going from each other.

175. **Musical Sounds.** — The human ear is acted upon by waves which have a frequency lying between two extremes which vary slightly with the individual tested. The lowest frequency easily audible to the human ear is about 30 and the highest about 30,000 vibrations per second. When a number of fundamental sounds or tones, each of a different pitch, are produced *consecutively* and the effect upon the ear is pleasing, the result is called *melody*, but when the tones are produced at the same time the result, if pleasing, is called *harmony*. In both cases

to produce this pleasing result the vibration frequencies must be to each other in the ratio of small whole numbers. This ratio between the frequencies of any two tones is called the *interval* between the tones. A musical *interval* then is *a ratio* between and not a difference between vibrations. A combination of tones or a very rapid succession of tones which do not bear to each other the simple ratios of musical intervals produces an effect known as *discord or noise.*

176. **The Major Diatonic Scale.** — In speaking, our tones change their pitch gradually; that is, they glide into each other, but in music the alteration of pitch takes place by successive and well-defined steps or intervals. The particular succession of intervals given below constitutes the major diatonic or natural musical scale. Any convenient number of vibrations may be selected as the lowest, or keynote, of this scale, but makers of physical apparatus usually select for tuning forks, etc., 256 vibrations per second for "middle C," while piano makers and musicians use 261, the international standard, or some even a higher number. Using the number 256 for C, the successive notes in an octave of the diatonic scale are related as follows:

Key of C	C	D	E	F	G	A	B	C′
Vib. No.	256	288	320	341.3	384	426.6	480	512
Ratio to C	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

This scale can readily be continued upward or downward by noting that the upper note in any octave is the lowest note in the next octave above, and that the notes in any octave bear the same relation to each other as those in the octave given.

If we select any other note instead of C as the keynote and construct a major diatonic scale, using the same ratios as those given above, we find that we obtain different vibration frequencies for many of the notes of the same name. For example, with the key of D we obtain the following values;

Key of D	D	E	F	G	A	B	C	D'
Vib. No.	288	324	360	384	432	480	540	576
Ratio to D	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

Upon comparing their vibration frequencies we find that many of the notes in the one scale do not agree in pitch with the notes of the same names in the other. From this it is evident that any instrument with a keyboard representing notes tuned correctly for one keynote, would be "out of tune" for music written in another key. On this account piano tuners are compelled to "temper" the scale by tuning the instrument in such a way that it is not exactly true to any particular keynote nor much out of tune for any.

177. **The Interference of Sound Waves called Beats.** — If we attach a piece of wax to one of two tuning forks having the same pitch and set both forks into vibration, the one having the extra mass to stop and start will vibrate at a slightly lower rate than the other. We thus obtain an alternation of loud and weak sounds known as *beats*. Probably on account of their tiring effect upon the nerves, these beats are very disagreeable. They are produced by the alternate interference and agreement of the waves with slightly different wave length, as shown by the drawing (Fig. 254) in which the waves interfere at the center.

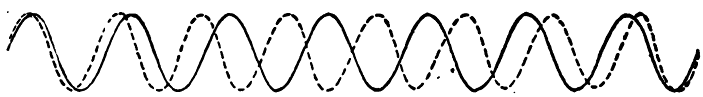


Fig. 254. — Diagram showing origin of beats. The two vibrations have frequencies whose ratio is 7 : 8.

If the waves are of equal energy when they interfere they neutralize each other, but when they are in agreement their combined effect is their sum. If one note has 256 and the other 255 vibrations per second, they will agree and interfere exactly once per second. Whenever there is a wide difference between the wave lengths, the beats become too frequent to be

distinguishable from each other and the disagreeable effect disappears.

178. **Overtones and Harmonics.** — Most vibrating bodies, such as strings and bells, produce at the same time a combination of tones of different frequencies or pitch. We have referred to the fact that the tone of the lowest frequency is the fundamental. The tones of higher pitch which are produced along with any fundamental are known as its *overtones*, and those overtones that have frequencies which are exact multiples of the fundamental are called its *harmonics*. The harmonics of "middle *C*" (256) are thus notes which have 512, 768, 1024, etc., vibrations per second.

179. **The Quality of Tones or Timbre.** — By the ear alone we can generally distinguish a tone or note of a given pitch, produced on one kind of musical instrument, say the piano, from the tone of the same pitch produced on any other instrument, for example, a cornet. This difference between the tones is expressed by saying that they have a different *quality* or *timbre*. Analysis shows that the quality of a tone is due chiefly to the number and relative strength of the *overtones* present in combination with the fundamental. Hence the quality of tone of a singer's or speaker's voice is due to the overtones as well as to the fundamental. The human voice, at its best, is particularly rich in harmonic overtones, but not infrequently, for various reasons, some of which are entirely under the control of the individual, the overtones of a speaker are not harmonics but discordant, thus producing an unpleasant voice.

180. **The Analysis of Sounds by Manometric Flames.** — The complex character of most sounds can be readily shown by the use of a simple device which produces a variation in the height of a gas flame by changes in pressure, hence the name *manometric flames*. The apparatus (Fig. 255) consists of a small box which is separated into two compartments *A* and *B* by a partition of sheet rubber or other substance sensitive to pressure.

Illuminating gas is admitted into one compartment A and lighted at the burner above. When the pressure in the air compartment B is constant the flame is of a uniform height. A sudden increase of the pressure in the air chamber will push the partition toward A, send a puff of gas out of the burner and increase the length of the flame. On the other hand, with a sudden decrease of pressure in B the partition will move away from A, diminish

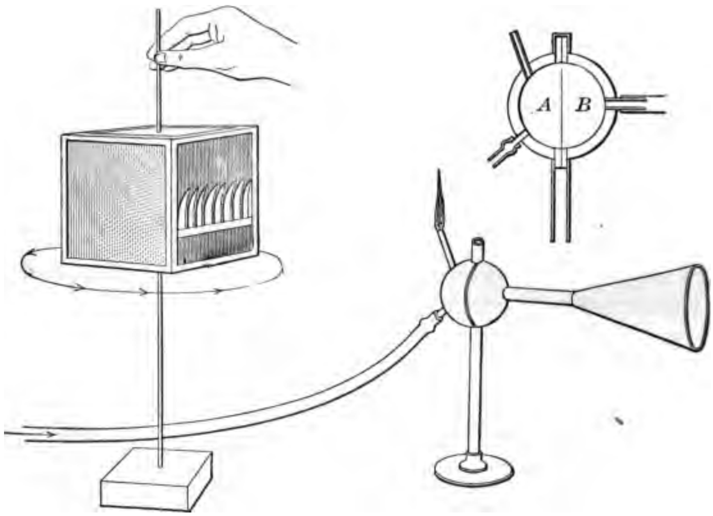


FIG. 255. — A manometric flame apparatus. Sound waves entering the cone produce a variation in the height of the flame, which can be observed by means of the rotating mirror.

the pressure there and the flame will be shortened. Sound waves entering the cone, with their alternation of condensation and rarefaction, will produce the increase and decrease of pressure in B necessary to give the variation in the height of the flame. These follow each other so quickly that the eye cannot detect them when looking directly at the flame. But if we now rotate a cubical mirror around a vertical axis and view the reflection of the flames we can distinguish the successive flames from each other. When no sound is produced, the

reflected light appears as a uniform band of light. A fundamental with no overtones produces an effect such as that shown in the first and second drawings (Fig. 256), but a combination of overtones with the fundamental gives results as shown in the third and fourth case. The more complex the sound waves are the greater is the variety shown in the motion of the flame, hence we may use this flame to determine roughly the character of sounds in respect to pitch, quality, and relative loudness.

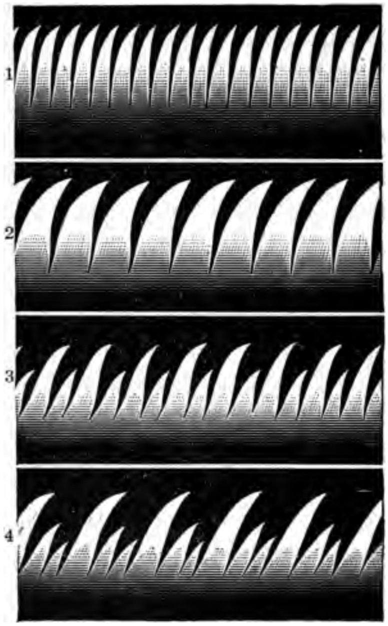


FIG. 256. — Manometric flames.

181. Musical Instruments; Stringed Instruments. — The common musical instruments may be considered under two classes — stringed instruments and wind instruments. This, of course, would not include such instruments as the drum, cymbals, etc., which produce tones more or less irregular in their character.

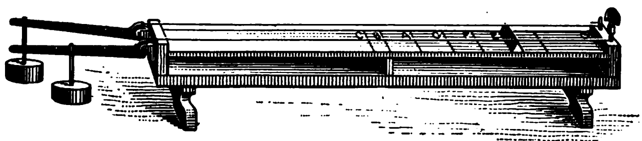


FIG. 257.

The laws of vibration of strings can be readily studied by means of the sonometer or monochord shown in Figure 257. This apparatus consists of a box along the top of which is

stretched one or more strings, by means of a weight or spring balance. At each end is a fixed bridge which determines the greatest length of the vibrating portion of the string. By means of an additional sliding bridge any desired portion of the string may be used. The pull of the attached weight or of the spring balance is called the tension on the string. Experiments with the sonometer have established the following laws of vibration for strings:

(1) *The vibration frequency, or pitch, varies directly as the square root of the tension on the string, other things being unchanged.* For example, if a tension of 4 lb. on a given string produces a tone of 128 vibrations per second, 16 lb. of tension would be required to raise the pitch one octave or to produce 256 vibrations per second.

(2) *The vibration frequency varies inversely as the length of the vibrating portion of a given string, other things being constant.*

With a constant tension on the string the pitch is raised an octave by putting the movable bridge halfway between the fixed bridges.

(3) *The vibration frequencies vary inversely as the square roots of the masses of the strings employed, provided they have the same tension and length.* Very low notes on pianos are produced by wires which have been increased in mass by the coiling of other wires around them.

Simple experiments show that strings may vibrate as a whole, producing the fundamental tone, and they may, at the same time, vibrate in halves, thirds, fourths, etc., thus giving the *harmonics* or multiples of the frequency of the fundamental. The particular place and manner in which the string is plucked, bowed, or struck determine the character of these overtones. On this account and because the length of the vibrating portion of the strings can be changed so easily and so much, the violin is capable of furnishing such a wide range of tones in respect to both quality and pitch.

182. Wind Instruments. — In these instruments the vibrations are produced by blowing a current of air (1) against a sharp edge, (2) through a reed, or (3) between membranous bands. Examples of these are (1) the flute and the flute organ pipe, (2) the reed organ and the clarinet, (3) the cornet and trumpet, in which the lips of the player by their vibration originate the sound.

In all those instruments where pipes or tubes are used, the pitch and quality of the fundamental is determined largely by the dimensions and material of the tube or pipe. The simplest of these is the flute organ pipe (Fig. 259), where the sound is produced by the air striking against the sharp edge L as it issues from the tube below. The air is thus thrown directly into vibration. The greater the length of the tube the lower the pitch of the fundamental. Closing the tube at the top also lowers the pitch. It can be shown experimentally that the fundamental tone of an open pipe has a wave length which is twice the length of the pipe; or the length of the open pipe represents $\frac{1}{2}$ the wave length as shown in Figure 259. The fundamental of a closed pipe is an octave lower, and has a wave length equal to four times the length of the pipe, or the length of a closed pipe is $\frac{1}{4}$ of the wave length of the fundamental.

Nodes and Loops. — If a coil of wire or a flexible cord is fixed at one end and the other end is thrown into vibration by the hand as shown in

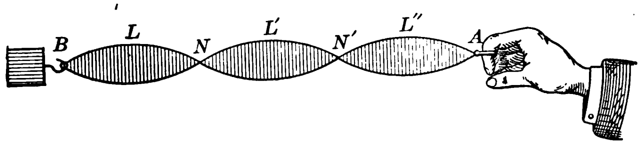


FIG. 258. — Showing nodes N, N', and loops L, L', L''.

Figure 258, the motion of the hand may be so regulated that the waves reflected from the fixed end will meet the direct waves in such a manner that the cord is practically at rest at a certain number of points N, N'. These points of no motion are called *nodes* and those of greatest amplitude, L, L', L'' are called *loops*. The distance from one node to another is $\frac{1}{2}$ the wave length.

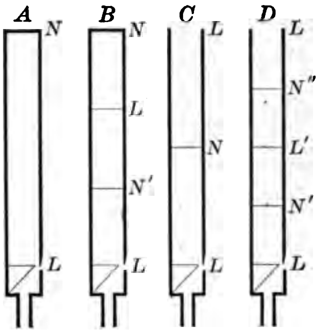


FIG. 259. — Showing nodes N and loops L in open and closed pipes.

Nodes and loops are also produced in organ pipes and in the tube of the whistle (Fig. 243). In connection with air vibrations a node is a place where the air particles remain at rest, but where, on account of the air on both sides rushing alternately toward and from it, there is the most rapid change from a condensation to a rarefaction. A loop, on the other hand, is a point where there is the greatest vibrating motion of the air but no change in its density. The closed end of a pipe must consequently form a node and the open end a loop, from which it follows that the wave length of a fundamental is 4 times the length of a closed pipe (A, Fig. 259) and 2 times the length of the open pipe (C, Fig. 259).

183. **The Phonograph.** — The phonograph presents a very interesting application of the principles of sound vibration and sound production. The chief features of this instrument are (1) a vibrating disk or diaphragm, and (2) a rotating cylinder of some soft material. The " record " is produced by so placing the vibrating disk that a metal point or chisel attached to it rests against the rotating cylinder. The speaker's voice or other sound sets the disk into vibrations and the little point attached to it traces a spiral path around the cylinder, thus producing the " record." The ups and downs in this path correspond to the original vibration of the disk; hence if the cylinder is placed in another machine so that the metal point of its disk may travel over the same path as the first, this disk will be thrown into vibrations and reproduce sounds which are fairly accurate imitations of the original.

Questions and Problems

1. Explain the rattling of windows which frequently accompanies thunder.
2. Why is it more difficult to hear a speaker's voice at a given distance in the open air than it is in a room or narrow street?

3. Explain the ear trumpet, speaking tube, and megaphone.

4. How long after he shouts will a boy have to wait to hear the the echo of his voice from a wood $\frac{1}{4}$ mile distant?

5. On what two things does the velocity of a wave depend? What is the relation of temperature to each of the two?

6. On what kind of days can you hear a given steam whistle the greatest distance — clear or cloudy? Calm or windy? When the temperature is nearly constant or rapidly changing? From a study of these conditions state your conclusions as to the atmospheric conditions which are favorable to the transmission of sound waves.

7. If the interval between a lightning flash and the thunder is 2 sec., how far is the lightning from the observer when the air temperature is 30° F.?

8. Define wave length, amplitude, period, and frequency.

9. A person firing a gun hears the echo from a distant hill 5 sec. after the discharge. How far distant is the hill, the temperature being 70° F.?

10. If the velocity of a certain sound is 1100 ft. per second and the vibration frequency 200 per second, what is the wave length? The period?

11. A certain note has 256 vibrations per second. Find the velocity if the wave length is 4 ft. What effect will an increase in the temperature of the air have upon the wave length? Why?

12. What is the relation between the wave length of a given note and the wave length of a note an octave above it? Would this relation be true if the waves were in different media? Explain.

13. Do all tones with the same pitch have the same frequency? The same velocity? The same wave length? (Include other media besides air.)

14. Find the period when the wave length is 1.5 ft. and the velocity 1088 ft. per second.

15. Explain why sound waves have less energy per square foot as they move away from the source, neglecting reflection.

16. Prove geometrically the "law of inverse squares." What effect does the wasted energy have upon the rate of decrease in intensity as shown by the law? Apply your conclusion to a block of wood and sawdust as the media for sound.

17. Explain the process known as "deadening" walls and ceilings.

18. In what way do the ground, walls, floors, modify the total intensity of sound waves at a distance from their source?

19. Name the characteristics of a sound wave which determine the character of the sensations known respectively as intensity, pitch, quality.

20. Explain how beats are produced.

21. How many beats per second are produced when one note has 350 and the other 354 vibrations per second?

22. The vibration frequency of a string 87 cm. long will bear what relation to that produced when only 29 cm. of it is allowed to vibrate? State the law involved.

23. If the tension on a certain string is 4 lb., to what must it be changed to raise the pitch of the note produced an octave higher? To lower the pitch an octave? State the law.

24. A string 80 cm. long vibrates 260 per second when under a tension of 40 k. What must be the tension that $\frac{1}{2}$ the length of string may give the same note?

25. Generally speaking, does sound travel faster in the morning or at noon? Faster on a mountain top or at the sea level? Give your reasons.

26. Air is compressed in a tube. From a consideration of the change in density and elasticity determine the effect upon the velocity of sound through the tube.

XIII. LIGHT

184. Two Meanings of the Term "Light." — The term *light* is most commonly used to denote *the physical cause* of the sensation of sight or vision, though occasionally we apply the term to the sensation itself. In a perfectly dark room we can see nothing; there is no sensation of sight, the external cause, light, being entirely absent. A perfectly blind person is also without this sensation even when surrounded by sunshine, for in his case the organ of sight, the eye, does not respond to the external cause. In the discussions which follow, unless we plainly indicate otherwise, we shall use the term *light* to indicate the physical cause of vision rather than the sensation itself.

185. The Nature of Light and of other Radiant Energy. — Light and radiant heat come to the earth from the sun and the most distant stars. The earth's atmosphere does not extend more than a few hundred miles above the sea level. Between the outermost portion of this atmosphere and the sun, a distance of more than 90,000,000 miles, the light travels even better than in the air itself. The bulb of the familiar incandescent electric light contains practically no gaseous matter in the space around the carbon thread, yet light and radiant heat are readily transmitted. These facts lead us to the conclusion that *light with other radiant energy is transmitted through a vacuum*, or through a space entirely devoid of ordinary matter, that is, matter as we know it under the terms *solid*, *liquid*, and *gas*. Many facts can be presented which, when understood, furnish convincing proof that all radiant energy is due to waves in a medium. For reasons already suggested, this medium, called the *luminiferous ether*, must extend throughout all space, completely

filling that which is called a vacuum, as well as the space between the molecules of all bodies. When light and radiant heat pass through air or glass, it is probably the ether between the molecules which transmits the energy, and not the air or glass molecules. Ordinary matter is only more or less of a hindrance to the transmission of ether waves. Because the medium for sound is ordinary matter, a sound wave cannot pass beyond the limits of the atmosphere, but a light wave originating on the earth is transmitted better after it gets beyond the limits of the atmosphere than when passing through it.

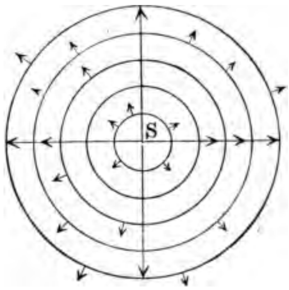


FIG. 260. — The waves originating at S move outward in all directions as shown The circles represent the waves which are really spherical shells having convex wave fronts.

186. The Shape of Light Waves; Rays. — When light originates from a point the wave fronts are spherical in form, provided the medium in which they are moving is uniform (Fig. 260). Any point on such a wave front is moving constantly away from the source along a radius of the sphere, hence the light is said to radiate in *straight lines.* The circles in the drawing represent the concentric spherical wave fronts, and the arrowheads show the directions in which the wave is going at the points where they are drawn. These radial lines along which the light is traveling are called *rays. A ray of light is then not a quantity of light, but simply the path of motion of any point of a wavefront.* The expression, " a collection or bundle of rays," is only a fiction sometimes used to denote a very small portion of a train of waves. When the source of light is very far away, as is the sun, any small portion of the light wave front is practically a plane surface, and the rays are said to be parallel. If, for any reason, any portion of a wave front becomes spherically concave (Fig. 261), the different points on the wave front will move toward

a common point F, and the light will finally be concentrated there. The point at which all or a considerable part of the energy in any wave front becomes concentrated is called the *focus*. This idea may also be expressed by saying the rays (directions) *converge* to a focus (Fig. 261). Similarly, we may say that the rays *diverge* in Figure 260. In geometrical constructions it is frequently simpler to use the method of rays, but clear thinking concerning radiant energy demands the conception of waves and wave fronts.

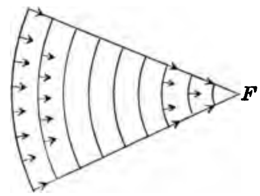


FIG. 261. — The wave fronts are concave.

187. The Velocity of Light. — According to the most reliable determinations the velocity of light, radiant heat, and other ether waves in air is about 186,500 miles per second. In empty space or pure ether its velocity is about 50 miles per second greater. In glass, water, and other transparent solids and liquids, the velocity of light is decidedly less than in air, a fact of great importance in explaining the action of prisms and lenses on light (sections 200 and 204). The enormous velocity of light can best be appreciated by comparing it with other velocities. A fast express train has a velocity of about 1 mile per minute or $\frac{1}{60}$ of a mile per second. A sound wave in air at 0° C. has a velocity of about 1090 ft. or a little over $\frac{1}{5}$ of a mile per second. Sound waves, therefore, travel about 12 times and light waves about 11,000,000 times as fast as an express train, a velocity sufficiently great to carry a body $7\frac{1}{2}$ times around the earth in 1 sec. On this account the time taken for light to travel short distances on the earth is so small that it may generally be neglected.

188. The Astronomical Method of Measuring the Velocity of Light. — The velocity of light is so very great that Galileo and other early experimenters failed to discover that time is actually required for its transmission. It was not until 1675 that Roemer, a Danish astronomer,

first proved that ether waves are not transmitted instantaneously. His method is based upon the fact that as a certain moon m (Fig. 262), of Jupiter revolves around that planet j it becomes eclipsed or hidden from an observer on the earth e. The time required for the moon to go entirely around Jupiter is always the same, but Roemer found that the observed time between any two successive eclipses was greater than the average when the earth was at e'' and less than the average time

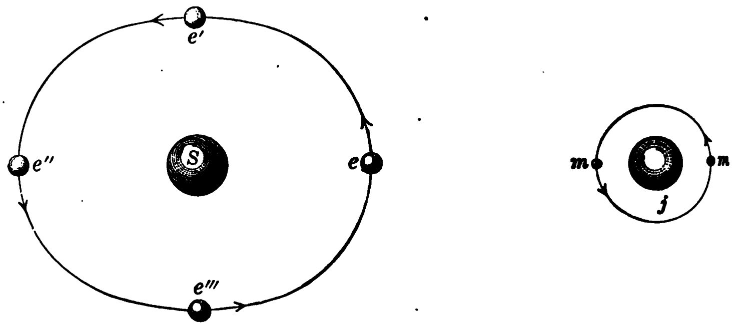


FIG. 262.

if the earth was at or near e'''. When the earth is at or near e' it is moving rapidly away from, and when it is at e''' it is moving rapidly toward Jupiter. When the earth is at e' the time between two successive eclipses will be as much greater than the average as the length of time required for the light to travel the distance the earth has moved away from Jupiter since the last eclipse. By a similar line of reasoning it can be shown that as the earth is approaching Jupiter at e''' the interval between the eclipses will be correspondingly shortened. In this manner Roemer showed that light required about 1000 sec. to cross the earth's orbit, e to e'', a distance now known to be about 186,000,000 mi. Hence, the velocity of light is about $\frac{186000000}{1000}$ = 186,000 mi. per second.

189. On Certain Terms used in Connection with Light. — A *self-luminous* body is one which generates light; that is, it converts some other kind of energy into light. The sun, a flame, a glowing coal, are familiar examples of self-luminous bodies. Most bodies are *non-luminous;* they can be seen only by the light which they first receive from other bodies, and then reflect to the eye; hence they are invisible when in a dark room. Bodies which transmit light, that is, allow light to pass through,

in a sufficiently definite manner to produce vision are called *transparent*. Familiar examples are air, pure water, glass, and mica. If a substance transmits light, but not so as to permit a person to see through it, the object is called *translucent;* familiar examples are paper, ground glass, and milk. A body which does not transmit light at all is said to be *opaque*. The distinction between translucent and transparent is not sharply drawn. That portion of the light or other radiant energy that enters a medium and is not transmitted is said to be *absorbed*, that is, it is converted into heat.

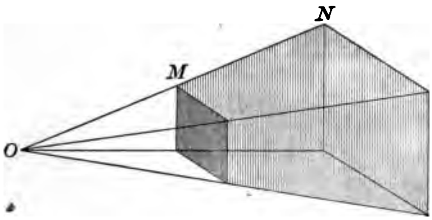


FIG. 263. — Showing the shadow region of the body *M*.

190. Shadows. — If light originates at a point *O* as in Figure 263, and an opaque card is held at *M* and a larger screen at *N*, that portion of the wave train which falls upon *M* will be lacking in the space between *M* and *N*. This space which receives no light from *O* is called the shadow of *M*. The extent of the shadow can be found by drawing lines from *O* to the boundaries of *M* as shown. We often think of the absence of light on the *screen* as constituting the entire shadow, but the shadow exists throughout the space between *M* and *N*.

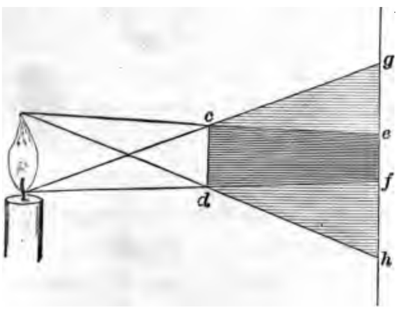


FIG. 264. — Showing the difference between the umbra *ef* and the penumbra *eg* and *fh*.

Most luminous objects emit light from a large number of points and the character of the shadow is thus considerably modified. When a coin is held between a candle or gas flame

and the wall, the shadow on the wall will be distinct only when the coin is very near the wall; in the other positions the shadow will be such as is shown in Figure 264 or in Figure 265. In Figure 264 light from one or more points of the flame reaches the wall at all its points except at those between *e* and *f*. The region *c*, *e*, *f*, *d*, into which no light comes, is called the *umbra*, and the surrounding region from which only a part of the light is cut off is called the *penumbra*. Since the object is smaller than the source of the light and relatively distant from the wall, the cone-shaped umbra does not reach the wall in Figure 265.

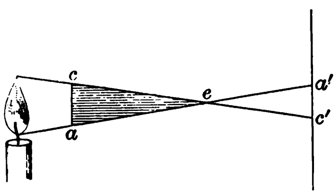


FIG. 265. — No point on the screen *a′c′* is entirely deprived of light from the candle.

In a total eclipse of the sun the umbra or complete shadow of the moon reaches the earth at certain places, thus depriving those places of all direct sunshine for a brief period. The penumbra, being much larger, affords a partial eclipse to a much larger part of the earth and for a longer time.

191. **Vision.** — The particular form of energy which acts upon the eye is called light. Strictly speaking, we cannot see anything but light, just as the only thing which we can hear is sound. When we say we "see books" and "hear pianos" we mean that through the eye and the ear we become conscious of the wave energy which each sends to us. In order to "see an object," light waves must come from the object seen into the eye of the observer. *Looking* consists in merely directing our eyes properly and giving attention to the effect produced by the light which enters them. In so far as concerns the person, the physical part of seeing, like hearing, is a passive rather than an active process. Since light commonly goes in straight lines from the object to the eye, we naturally infer that the different parts of the object seen, — object sending the light, — are each somewhere back along the straight lines in which the light was

traveling when it entered the eye. This inference is generally correct, but not infrequently the light, by reflection or otherwise, has experienced a change in direction on the way from the object to the eye, and then this inference concerning the position of the body is likely to be wrong. When we stand before a mirror we see our own faces just as truly as we ever see another person's face. In each case seeing is accomplished by the light which comes from the face into the eye of the observer, though in one case it comes directly and in the other by way of the mirror. On account of the changed direction the light seems to come from behind the mirror, and only our experience convinces us that it does not. A change in the direction of light, produced without the knowledge of the observer, is the basis of many stage tricks.

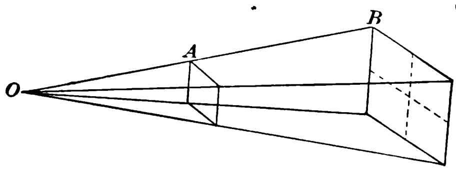


FIG. 266. — The intensity of light at B is $\frac{1}{4}$ as great as it is at A.

192. The Intensity of Illumination; its Relation to Distance.— The amount of light energy per unit of surface, called the intensity of the illumination, depends upon two things, (1) the distance of the given surface from the source of light, and (2) the rate at which the source or luminous body is producing light energy.

The relation of intensity to distance from the source can be readily shown by experiments with a very small source of light and opaque screens as shown in Figure 266. Screen A, placed 20 cm. from the source O, will cast a shadow 4 times as large as itself on screen B, which is 40 cm., or twice as far from the source. Since all the light which falls on A would fall on B if A were removed, it follows that on 1 cm.^{2} of the surface at A there must be 4 times as much light as on 1 cm.^{2} at B. That is, the intensity at A is to the intensity at B as 4 : 1. But the numbers, 1 and 4, bear the same relation to each other

as the squares of the distance $(20)^2$ $(40)^2$, hence *the intensity of the illumination varies inversely as the square of the distance from the source.*

Remembering that light waves are spherical and that the surface of a sphere increases as the square of its radius, the explanation of this law of intensity is easily understood. For example, the areas of the spheres which have the radii 20 cm., 40 cm., are to each other as $(20)^2 : (40)^2$, or as $1 : 4$. But the radii, the distances from the source, are as $1 : 2$. Hence the intensities which are to each other as $4 : 1$ are to each other inversely as the squares of the distances from the source. In general, as any light wave advances, its energy is being distributed over a surface which increases *directly* as the square of the distance the wave has traveled; hence, the amount per square centimeter, the intensity of the light, varies *inversely* as the square of the distance from the luminous body or source. It must be noted that this law of intensity applies only to the *direct light* from a luminous body; for the total illumination on a given surface is usually very much increased by the light reflected from near-by non-luminous bodies. On this account white walls and light-colored furnishings add considerably to the total intensity of the light in a room.

193. **Intensity of Sources of Light; Illuminating Power; Photometry.** — It has already been stated that the intensity of the illumination at any surface depends not only upon the distance from the source, but also upon *the rate at which the source produces light energy*, known as the *illuminating power*. The common, though by no means satisfactory, unit of illuminating power is called the "candle power." The British standard candle power is the rate at which light is emitted by the flame of a sperm candle weighing $\frac{1}{6}$ of a pound and burning 120 grains per hour. It has been shown, however, that the amount of light emitted by such a candle may fluctuate through a range

of 20 per cent or more. The determination of the *relative illuminating power* of different sources of light is a matter of great practical importance, since quantity of light emitted in a unit of time is one of the factors in determining the commercial value of any kind of artificial light. Instruments for comparing the illuminating powers of two sources are called *photometers*. The two most common forms are those known as Rumford's and Bunsen's photometers, both of which depend upon the law of inverse squares.

It has already been shown that the intensity of illumination, at different distances from a constant source of light, varies *inversely* as the square of the distances from that source. If the distance between the source and a given surface changes, in order to keep a constant illumination on that surface the illuminating power at the source must vary *directly* as the square of the distance. *Consequently when two different luminous bodies throw light of the same intensity upon a given surface the intensities at the sources, or the illuminating powers, are to each other directly as the squares of the distances from the sources to the given surface.*

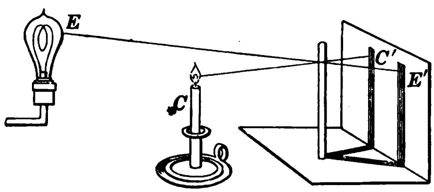


FIG. 267. — Rumford's method of measuring relative illuminating power.

Rumford's photometer involves a comparison of shadows (Fig. 267). Two shadows of the same object are produced side by side, and the sources moved in relation to the screen until the eye decides that the shadows seem equally dark. Since each source illuminates alone that part of the screen on which the shadow of the other falls, when the shadows are alike the intensities at the screen are the same. Then by measuring the distances from the screen to the two sources, the relative intensities at the sources can be found as shown above.

In Bunsen's form, shown in Figure 268, the opposite sides of a piece of paper having a small grease spot are illuminated at the same time by the two sources of light. The paper screen is moved back and forth until the spot has the same appearance, indicating equal illumination, on both sides. Then having

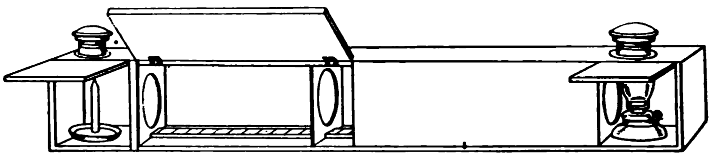


FIG. 268. — Bunsen's photometer.

measured the distance from each source to the screen, the relative intensities may be found by the same law as given for the Rumford form. It is worth noting that the value of a source of light for illuminating purposes depends upon the color and steadiness of the light emitted as well as upon its illuminating power.

194. **Images.** — If a pin hole is made in a thin sheet of metal or other opaque body, and a candle flame or a highly illuminated body is placed near the opening, the light from the different points of the candle will pass through the hole as shown in Figure 269 and, falling upon a screen, will there produce a dim but fairly clear image of the candle. (To secure good results no other light should fall upon the screen.) The formation of the image is easily understood, for it is evident that the light from each point of the candle goes straight through the hole and falls on a particular point on the screen. Since the hole

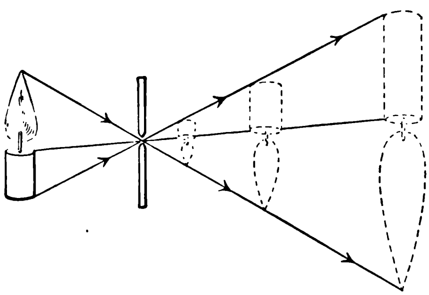


FIG. 269. — A real image produced by means of a pin hole.

is a small circle and not an exact point, there is some overlapping, on the screen, of the circular images of neighboring points in the object. If the hole is enlarged more light is let through, and the image becomes brighter but less sharply defined, for more overlapping of the light occurs. In order to produce a well-defined image by this method the hole must be very small and the image consequently very dim. It will be shown later (section 198 and section 206) that by other methods a much larger *portion of the light waves from one point of an object can be brought to one point again.* When this has been done, the *second point* is also called *the image of the first. The image of an entire body can be produced by thus forming an image of each of its points.*

Questions and Problems

1. When a carpenter looks along the edge of a board to determine whether it is straight, what fact regarding light is he using?

2. A tree 100 ft. from a pin hole produces an image 6 in. high on a screen which is 4 ft. distant from and on the opposite side of the hole. How high is the tree? Make a drawing and explain.

3. Suppose that the screen is moved farther from the hole, will the image be larger or smaller? Brighter or less bright? Why?

4. When we see anything, what acts and what is acted upon? Why is vision impossible to every person when the objects he is trying to see are in total darkness? Why is it impossible to a blind person even when he is in a good light?

5. Examine the shadow of a tall pole. At which end is the shadow more sharply defined? Explain.

Explain why a flying bird usually casts no shadow on the earth.

6. Is a flame seen by the light it generates or by that which it reflects?

7. Examine an ordinary incandescent or glow lamp before and after the current is turned on. In which case is the carbon thread or filament seen by the light it generates? How is it seen in the other case?

8. Burn a match and note (*a*) the flame, (*b*) the glowing coal, (*c*) the ashes. In which of the three cases is light generated? In which is it necessary to have light furnished from an outside source to produce vision?

9. In using a Bunsen photometer equal illumination is produced when the test candle is 8 cm. and an electric lamp 60 cm. from the screen. Find the candle power of the lamp in terms of the candle used.

10. At what distance from a 16 candle power glow lamp will a book receive the same illumination as it receives when 450 cm. from a 75 candle power kerosene lamp?

11. Prove by a figure that the amount of light falling upon a book depends upon the angle which the page makes with the rays of light, as well as upon the candle power and the distance of the source.

195. The Reflection of Light; Law of Reflection. — If we hold a piece of flat glass in sunshine, it readily appears that light waves which are traveling through air are partly admitted and partly reflected when they strike the new material. *Light is similarly reflected* not only by mirrors and polished metals, but by *all substances if the velocity of light in the second medium, or substance which the light strikes, is different from the velocity in the first medium.* The character of the reflection and the amount of light reflected depend chiefly upon the kind of material and the condition of the surface. A smooth silver surface reflects nearly all the light in a very *regular* manner, whereas a rough black surface reflects very little and that in a most irregular way.

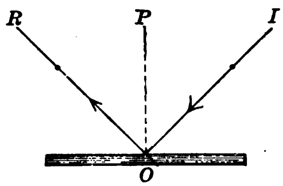


Fig. 270. — The angle of incidence IOP is equal to the angle of reflection ROP.

The Law of Reflection can be demonstrated in a simple manner: If a small portion of a direct wave of sunlight, often called a beam, is allowed to fall upon a plane mirror or other highly polished surface (Fig. 270.) the light I going toward the mirror is called the incident beam and the light R going from the mirror is called the reflected beam. Let PO be the perpendicular to the mirror at the point of incidence. Then, the angle IOP is called the *angle of incidence* and ROP the *angle of reflection.* A measurement of these angles in every case leads to the following law of reflection: *The angle of incidence is equal to the angle of reflection.* This law of reflection, though demonstrated here for plane waves only, is general, provided it be applied to the path of each point in the wave

front, that is, to individual rays. The perpendiculars to the various parts of a *rough surface* lie in so many different directions (Fig. 271) that the reflected light from such a surface may be said to pass off in all directions, producing *irregular* or *diffuse reflection.* Light thus reflected is generally called *diffused light.* This is the commonest kind of reflection and it is by this diffused or irregularly reflected light we are able to see most objects. Regularly reflected light from a surface hinders one from seeing that surface; hence, books and newspapers should not be printed on very smooth or glossy paper. The daylight in a room, except at such points as are reached by direct sunshine, is always diffused light, coming from a variety of objects both within and without the room. The gloss on paper is generally noticed more when artificial lights are used, unless they are surrounded by a translucent shade which diffuses the direct light which they otherwise emit.

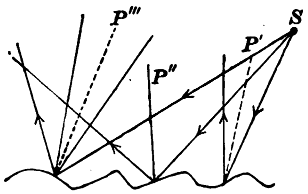


FIG. 271. — Since the perpendiculars P', P'', P''' are not parallel, the reflection of the light is irregular.

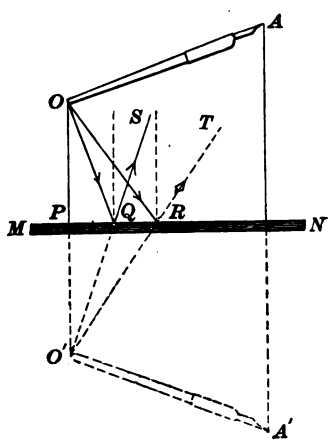


FIG. 272. — $O'A'$ is the virtual image of OA produced by the plane mirror MN.

196. The Reflection by a Plane Mirror of the Light from a Near Object; Virtual Image. — The reflection of a plane wave, or parallel rays, by a plane mirror has already been noticed. But when the light comes to such a mirror from a relatively near object, the waves from each point have convex fronts, or divergent rays, and the process of reflection is more complex. Let the line MN (Fig. 272) represent a plane mirror, the sur-

face of which is perpendicular to the plane of the paper (that is, a vertical mirror on a horizontal sheet of paper), and O any point in the object. From O draw several incident rays OP, OQ, OR, and their corresponding reflected rays PO, QS, and RT. If these lines, PO, QS, and RT are traced backward they will meet in the point O'. By simple geometrical reasoning it can be shown that OP and PO' are equal, hence the point O from which the reflected light seems to come is just as far back of the reflecting surface as O actually is in front of it. This is true also of all parts of the wave from O, whether they strike the mirror at P, Q, R, or at any other point.

All the light from O which strikes the mirror, *seems* to come from a point O' behind the mirror. This point O' from which the reflected light seems to come is called the *virtual* image of O. By a similar construction and demonstration, we can show that A' is the virtual image of A, and that *each point on the line $O'A'$ is the virtual image of a corresponding point of OA*. But the light from OA neither goes to $O'A'$ nor comes from it. *A virtual image, therefore, is one which only seems to be but actually is not formed.*

197. **The Character of a Virtual Image by a Plane Mirror.** — When the surface of an object is approximately parallel to the mirror, all points in the virtual image appear to be located on lines parallel to the mirror, at the same distance behind the mirror that the object is in front of it. Hence, when a person stands before a vertical mirror the virtual image of the right hand is opposite to the right hand, the image of his head opposite to his head, and so on for all parts of the body. The virtual image is erect and the parts of it are directed the same as are the corresponding parts in the body itself. But if we think of the image as an actual person facing us, then the right hand of the image seems to be on the left side of the body. We know that the right hand of a person who is facing us is opposi

o our left, hence, this image, in which the right hand is opposite o the right of the object, *is said to be a perverted image.* In this case the perversion is horizontal only, but when the mirror is at right angles to the object the perversion is vertical as well. The familiar reflection of trees by the surface of water (Fig. 273) is an excellent example of a virtual image perverted in both respects.

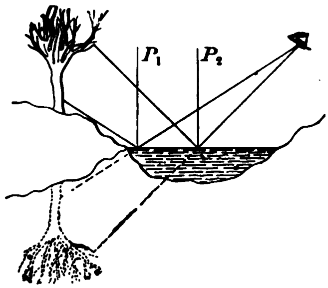


FIG. 273. — Showing the perverted image produced by the reflection of a water surface.

198. The Reflection by a Concave Spherical Mirror; A Real Image. — Let ABD (Fig. 274) represent a small portion of a highly polished sphere of which C is the center and CB that radius of the sphere which meets the polished surface or *mirror* at its central point B. The point C is known as the *center of curvature* and the line CB is the *principal axis* of the mirror. The parallel rays of a plane wave, after reflection from the concave surface, meet approximately at a point F halfway between B and C (Fig. 275). This point F is called the *principal focus of the spherical mirror.* If C were the source of light, the spherical convex wave front from C would strike upon ABD at all points in the direction of the perpendicular to the mirror at those points,

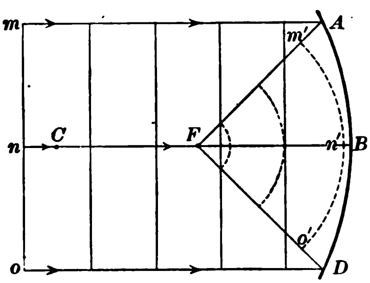


FIG. 274. — The plane waves mno, etc., after reflection become waves with concave wave fronts, $m'n'o'$, etc.

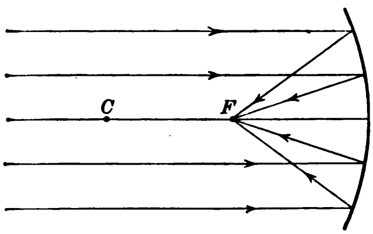


FIG. 275. — A principal focus by the use of rays.

hence the reflected wave front would be concave and the l[illegible] would return to the point C. For the same reason that portion of any wave, or a ray, which passes through C on its way to

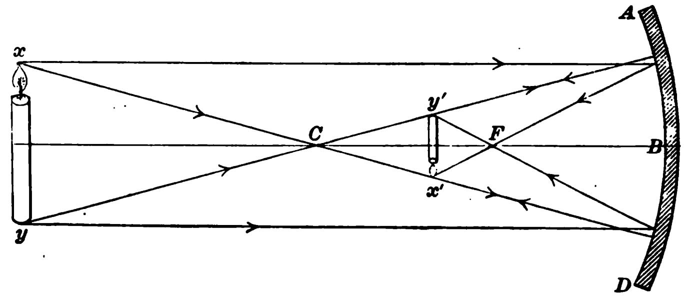


FIG. 276. — The concave mirror ABD forms an inverted real image of xy at $x'y'$.

the mirror will come back to C after reflection. Let xy (Fig. 276) represent an illuminated object at a greater distance from the mirror than is C. As already explained, that part of any wave or a ray which travels parallel to CB will be so reflected that it will pass through the principal focus F, and that part, or a ray, which goes through C will be reflected back toward C. At the point x', where these two rays meet, all other rays or portions of the wave from x will also meet, and there will be found the real image of x. Similarly we may show that the rays from y will meet at the point y', and thus we have located the two extreme points and determined the size of the inverted real image of the candle xy.

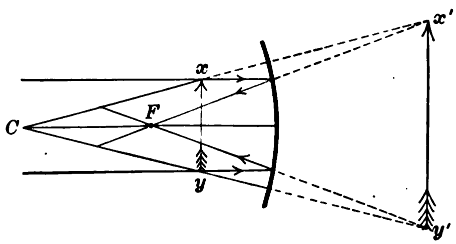


FIG. 277. — An erect virtual.

If the object xy is moved toward the center of curvature C, the image $x'y'$ will also approach C and increase in size, and finally when the object is at C the image and object will

practically coincide, provided the object is small compared to the size of the mirror. As the object is moved nearer to the mirror than C the image moves farther away and becomes larger than the object, until finally the image becomes infinitely distant, that is, ceases to exist when the object is at the principal focus, F. The reflected waves now have plane wave fronts or parallel rays. If the object is between F and the mirror, the reflected rays diverge and the result is now an enlarged virtual image, that is, the light leaves the mirror, as though it came from a larger object behind the mirror, as shown in Figure 277.

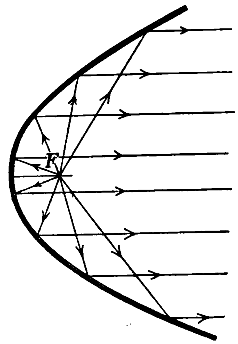


FIG. 278.—Section through a parabolic mirror having its principal focus at F.

As regards the relative size of object and image, that one of the two is always *larger* which is more *distant* from the mirror. It must be noted that the *real image is always inverted* and the *virtual image erect.* The demonstrations given above are only approximate. An error is involved in the assumption that by a means of a spherical mirror parallel rays or plane wave fronts will be reflected to a common point, the principal focus. For very small mirrors with a large radius of curvature, this error is small. But when large mirrors are used as reflectors, as is done in the search light where the electric arc is placed in the principal

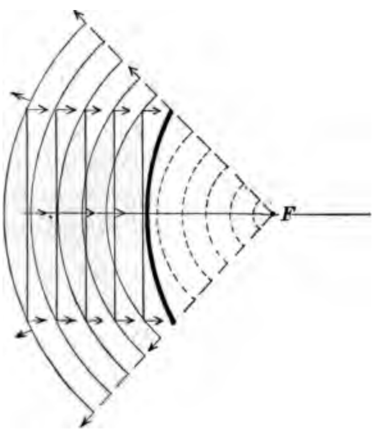


FIG. 279. — The plane waves are, by reflection, converted into convex waves, which seem to come from F.

focus, this variation of the focus, known as ***spherical aberration***, is so important that it becomes desirable to use another form of mirror known as the parabolic mirror, a section of which is shown in Figure 278.

199. The Convex Spherical Mirror. — A very simple construction (Figs. 279 and 280) shows that plane wave fronts, rays parallel, striking a convex mirror are converted on reflection into convex wave fronts, hence, the rays diverge as if they all came from a common point F, the virtual focus of the wave. Similarly a convex wave front falling upon a convex mirror is thus made still more convex, or the rays more divergent. Hence the light waves from a given point in a body could not be brought to a focus by a convex mirror though they would always seem to come from a point back of and nearer to the mirror than the *body* actually is. *Though a convex mirror cannot form a real image, it produces an erect and diminished virtual image of an object at any distance.*

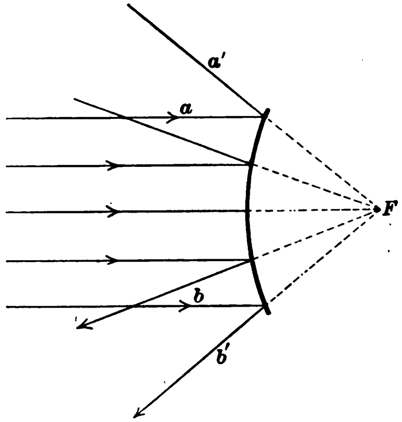


FIG. 280. — The reflection of parallel rays from a convex mirror.

Questions and Problems

1. Distinguish between regular and irregular reflection. By means of which do we see bodies which are not self-luminous or light producing?
2. Could a perfectly reflecting mirror be seen? Explain.
3. State the character and location of the so-called image produced by a plane mirror.
4 What is the relation between the distance of the image from the observer and the distance of the object from the observer? What effect does this have on the apparent size of the image?

5. Define the principal focus of a mirror; the principal axis; the center of curvature.

6. Distinguish between a real and a virtual image.

7. State the conditions under which a concave mirror may form a real image.

200. **Refraction of Light.** — We have already called attention to the fact that when a light wave in air comes to a new medium [1] a portion of the wave is reflected and the remainder admitted to that medium. If this new medium is opaque like wood or metal, the admitted light is either reflected out again or converted into heat before it has penetrated to an appreciable distance. But when the new medium is transparent like glass and water, the admitted waves travel a very considerable distance before much absorption takes place. A small beam of sunshine, or any other train of plane waves, allowed to strike upon a piece of glass perpendicular to its surface, as shown at A in Figure 281, will continue to move in the same direction, after entering. But when the light meets the glass at an angle to the perpendicular, as at B in Figure 281, the direction of the wave or rays will change both when passing into the glass at m, and again when passing into the air at n. *The abrupt change in the direction of light which occurs when a wave passes from one medium into another is called refraction. Refraction is produced only when there is a difference between the velocities of ether waves in the two media.*

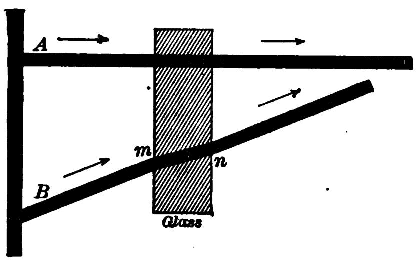


FIG. 281. — The beam A striking the glass perpendicularly is not refracted. The beam B is refracted at both m and n.

An Explanation of Refraction. — When a plane wave strikes

[1] Though the real medium for light is the ether, it is customary to speak of glass, water and other materials through which light is passing as the medium at that time.

a surface perpendicularly, the wave front will be parallel to the surface of the glass (A, Fig. 281), and the wave, though experiencing a decrease in velocity and wave length, moves in the same direction in the glass as in the air. Upon passing into the air again, if the sides of the glass are parallel, the wave, regaining its velocity and wave length, continues in the same direction as before entering the air. Thus we see why no refraction takes place when the light strikes a surface perpendicularly. If the direction of the beam is not perpendicular to the surface (Fig. 282), each wave front will meet the surface *ab* first at its lowest part or near *a*. Since both the velocity and wave length of light are less in glass than they are in air, that part of a wave which enters the glass first is retarded first, and the wave front is so changed that it passes through the glass in a different direction and with shorter wave length than it had in the air. At the instant of return to the air the lower portion of the wave gets into the air first, hence regains the original velocity, and thus restores to the wave front its original direction.

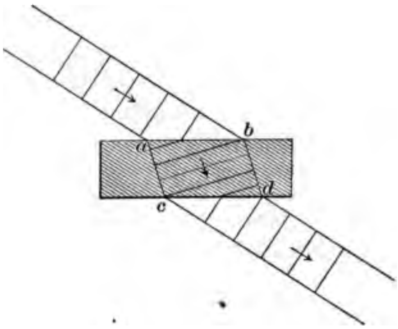


FIG. 282. — Both the velocity of the waves and their wave length are less in the glass than they are in the air.

201. Refraction of Light when passing through a Prism. — Let *ABC* (Fig. 283) represent an end or a sectional view of a glass prism. If a train of small plane waves falls upon the surface *AC*, the upper part of each wave is the last to enter the glass

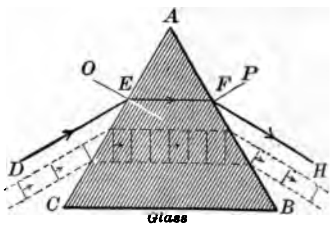


FIG. 283. — The refraction of light as it passes through a prism.

hence the wave front is turned downward as already explained. Upon arrival at the side AB, the upper part of the wave is the first to pass into the air, hence a second time it gains on the lower portion, that is, the wave is again refracted downward. We see that light in passing through a prism experiences a permanent change in direction because one part of each wave, the lower part in this case, travels through a greater thickness of glass and hence falls behind the other parts of the same wave, thus changing the direction of the wave front.

Though the explanation of refraction is more easily understood when presented by the use of waves, it is generally more convenient in our further discussions to use the method of rays. Let DE be a ray incident at E (Fig. 283). Since it does not meet the surface AC perpendicularly, it will be refracted, the amount of change in direction depending chiefly upon the angle of incidence and the relation between the velocity of light in air and its velocity in the glass. Since light has a less velocity in glass than it does in air, the ray DE will be refracted or turned toward the perpendicular OE (produced). Upon arriving at F, the ray returning to the air will be refracted from the perpendicular FP and move in the direction FH. If the light passing through the prism is a mixture of waves of different lengths, in addition to the refraction, a difference of color may be observed. This effect will be discussed in section 209.

202. The Index of Refraction; Laws of Refraction. — As stated, the velocity of light is greatest in a vacuum. The change in direction known as refraction depends, as we have said, upon the change in velocity of the wave when changing media. The ratio between the velocity of light in a vacuum and its velocity in a given substance is known as the index of refraction of that substance or,

$$\frac{\text{velocity of light in vacuum}}{\text{velocity of light in substance}} = \text{index of refraction of that substance.}$$

The accompanying table gives the index of refraction of some important transparent bodies:

Table showing the Relative Velocities, or Indices of Refraction, for Yellow Light

Air	1.0003
Water	1.3340
Crown glass	1.5240
Carbon disulphide	1.6240
Flint glass	1.6510
Diamond	2.4700

An inspection of the table shows that the index of refraction of air is so small that it may generally be neglected. The relative indices of refraction of any two substances may be obtained by finding the ratio between the two indices given in the table.

The Amount of Refraction.—It can be shown experimentally that the *amount of change in direction* experienced by any ray when passing from one medium to another, depends upon three things: (1) the relative index of refraction of the two media, (2) the angle of incidence, and (3) the wave length of the light. An exact statement of the laws connecting these factors cannot be given without the use of higher mathematics. Generally speaking, refraction is *increased* either by an *increase* in the *relative* index of refraction or by an *increase in the angle of incidence*, but the refraction is *decreased* by an *increase in the wave length of the light.*

Examples of refraction are furnished by many of the familiar effects of water, glass, and other transparent bodies upon the appearance of objects seen through them. The apparent bending of a straight stick when it is held obliquely in water and the distorted appearance of objects when seen through uneven window panes are well-known effects of refracti[illegible]
The refraction of air is shown by the familiar shimmer [illegible]

appearance of objects when seen through the unequally heated, and hence unequally refractive, air rising and mixing with the other air above a hot stove or engine, sometimes erroneously called "seeing the heat."

203. **The Critical Angle; Total Reflection.** — Let ABC (Fig. 284) represent half of a short glass cylinder, or disk, and D be the middle point of the plane surface AC. The ray of light BD, because it strikes perpendicularly both the curved surface ABC and the plane surface ADC, passes through the glass without being refracted. The ray ED is refracted at D, and continues in the air along the line DE'. Similarly, the ray FD is refracted along the line DF'. By increasing the angle between the incident ray and the normal BD, we finally reach a ray GD which has the greatest possible angle GDB with BD and yet be refracted, for the refracted light then passes along the surface ADC. This greatest possible incident angle at which any ray may strike a surface of a given medium and yet be refracted is called the *critical angle* of that medium.

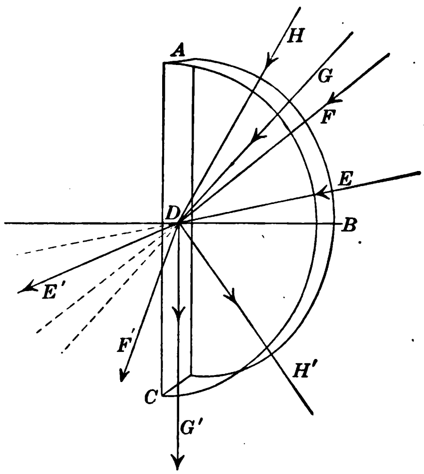


FIG. 284.—Angle GDB is the critical angle of the glass.

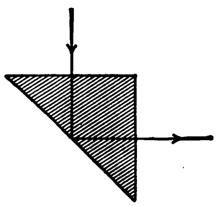


FIG. 285.—A totally reflecting prism.

For water the critical angle is about 48.5°, for the diamond 24°, and for glass it varies from 38° to 41°. Whenever the angle of incidence of any wave exceeds the critical angle, since none of the light can then pass out at the surface, the whole wave

is reflected according to the law of reflection. This is known as *total reflection.* Thus the ray HD (Fig. 284) is totally reflected along DH', as are all other rays between GD and AD. One of the simplest cases of total reflection is that shown by a glass prism having two equal faces meeting each other at right angles (Fig. 285). The incident ray makes an angle with the perpendicular greater than the critical angle, hence it is totally reflected, its direction being changed 90°. Another example of total reflection is shown in Figure 286. The small critical angle of the diamond makes possible the large amount of internal reflection which produces its brilliancy.

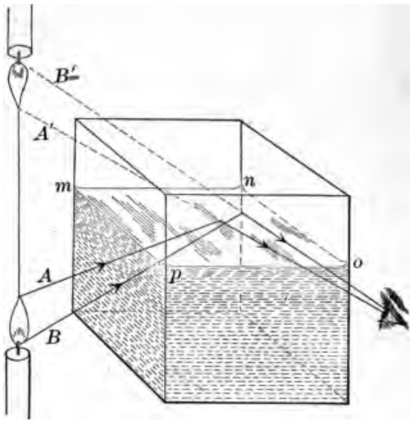


FIG. 286.—The rays A and B strike the surface *mnop* at an angle greater than the critical angle of the water, hence they are totally reflected and appear to come from $A'B'$.

QUESTIONS AND PROBLEMS

1. Compute the relative index of refraction when light is passing (*a*) from water into crown glass, (*b*) from flint glass into diamond.
2. Taking the velocity of light as 186,000 mi. per second in air, find by means of the indices of refraction its velocity (*a*) in flint glass, (*b*) in water.
3. Upon what things does the amount of refraction in any case depend? Upon what does the index of refraction depend?
4. Other things being the same, will light be refracted more when going from air into a glass prism or from water into the same prism? How many times as much?

204. Lenses.—Any transparent body bounded by two curved or one plane and one curved surface is called a *lens.* Each curved surface is usually a portion of a sphere and the lens is then called a *spherical* lens. There are two types of the spherical lens: (1) those which are thicker through the middle

than at the edges, called the convex lenses, shown in section 1, 2, 3 (Fig. 287), and (2) those which are thinner through the middle than around the edges, called the concave lenses, 4, 5, 6 (Fig. 287). If both surfaces of a lens are spherical, the *line* (*DC*, Fig. 288), connecting the centers of the two spheres of which these surfaces are parts, is called the *principal axis* of the lens. If one surface is spherical and the other plane, the principal axis is the line drawn from the center of the sphere perpendicular to the plane. In every lens there is a

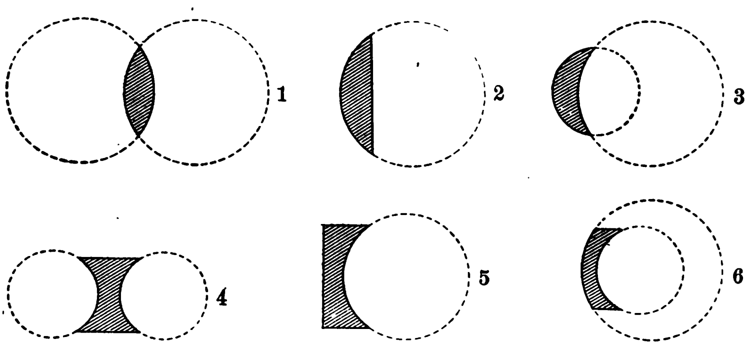


FIG. 287.—Showing the varieties of each of the two types of lenses.

point on the principal axis so situated that all portions of the waves, or all rays, passing through it, suffer no change in direction. This point is called the *optical center* of the lens. In a symmetrical lens, that is, one with the same curvature on both sides, the optical center is the center of volume. Any straight line passing through the optical center at an angle with the principal axis is called a *secondary axis*.

205. The Action of Convex Lenses on Light Waves. — A beam of sunshine or any other train of plane waves moving parallel to the principal axis will be brought to a focus by a convex lens at a certain point *F*, as shown in Figure 288. For, since the center of the lens is much thicker than the edges, and the velocity of light is less in glass than it is in air, those

portions of each wave which pass through the center are retarded more than are the other portions which pass through the thinner parts of the lens. For this reason the plane wave fronts become concave and, because all parts of the wave are then directed toward a common point F, the light energy becomes concentrated or focused there. The point on the principal axis at which plane waves are focused is called the *principal focus* of the lens. For plane waves moving in the opposite direction there is evidently a corresponding principal focus on the other side of the lens. But light proceeding from the principal focus F approaches the lens with convex wave fronts, and emerges from it with flat or plane wave fronts. The same ideas are intended to be expressed by Figure 289, where rays are used instead of wave fronts. The parallel rays are brought to the principal focus F, and rays diverging from F are rendered parallel by passing through the lens.

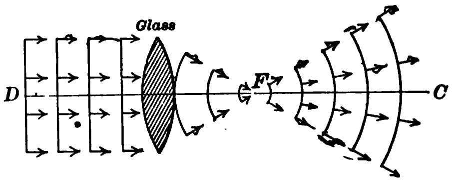


Fig. 288.—The plane wave fronts are made concave by the lens. After leaving the focus they are convex.

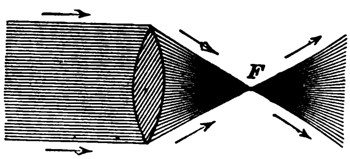


Fig. 289.—A principal focus, shown by means of rays.

If the light comes from a source S' comparatively near, yet at a distance from the lens greater than the principal focal length, these waves also emerge from the lens as concave waves but less concave than are those which enter as plane waves, hence their focus S'' (Fig. 290) is farther from the lens than the principal focus. The nearer S' comes to the lens the farther S'' will be from it. It is

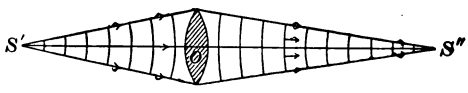


Fig. 290.—Conjugate foci S' and S'', shown by both waves and rays.

evident that light originating at S'' would come to a focus at S'. Any two points, bearing such a relation to each other that light originating at either point will come to a focus at the other, are called *conjugate foci*.

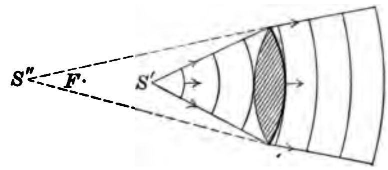


FIG. 291.—The source of light S' is nearer to the lens than is the principal focus. S'' is the virtual focus of S'.

The same idea is expressed by saying that the divergent rays from S' are converted into convergent rays which meet at the conjugate focus S''.

Let us next consider the case when the source of light is placed at a less distance from a convex lens than its principal focal length (Fig. 291). The wave fronts originating at S' are now so convex at the time of striking that the refractive power of the lens is no longer able to convert them into concave wave fronts; they do not come to a focus. Nevertheless they issue from the lens much less convex than when they entered it, and consequently seem to come from a point S'' more distant from the lens than is their source. This point from which the light *seems* to diverge is called the *virtual focus* of S'. A virtual focus is shown by means of rays in Figure 292.

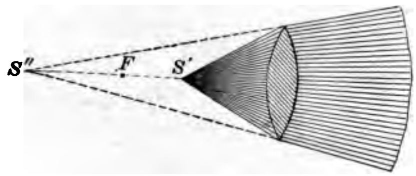


FIG. 292.—A virtual focus shown by means of rays.

206. The Formation of an Image by a Convex Lens. *A Real Image.*—Let MN (Fig. 293) represent an object at a distance from the lens greater than its principal focal length. Let line XX' be the principal axis, and O the optical center of the lens.

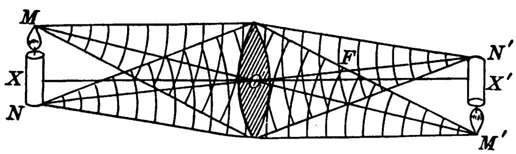


FIG. 293.—The formation of a real image by a convex lens, shown by means of wave fronts.

All the light from the point X which falls upon the lens will be brought to a focus X at the point X', the conjugate focus of X as already explained (Fig. 290). Similarly, the light from point M will be brought to a focus at M', and that from point N at the point N', for M' and N' are respectively the conjugate foci of M and N on the secondary axes MM' and NN'. Between M' and N' there is a succession of points, each of which is the image of a corresponding point in the body MN. Hence if a white screen is placed at $M'N'$, there will be formed on it an inverted real image of the object MN. Using the method of rays, the construction is simpler (Fig. 294). That portion of the wave or the ray MO which goes through the optical center goes approximately straight through the lens. The ray which is parallel to the principal axis XX' is so refracted that it goes to the principal focus; hence, where this and the ray through the optical center meet, all others from the same point also meet, and M' will then be the image of M. Similarly, we can show that N' is the image of N, and each point of $M'N'$ an image of a corresponding point in MN.

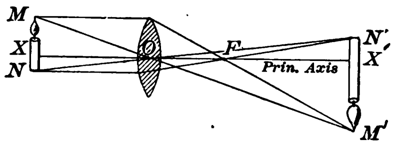


FIG. 294. — A real image shown by means of rays.

Experimentally, it can be shown that the relative sizes of object and real image depend, as mentioned in connection with mirrors, upon their relative distances from the lens, that one being larger which is more distant.

A Virtual Image. — When the distance from the object to the lens is less than the principal focal length, though it makes the waves less convex, the lens cannot now bring any of the light to a focus and consequently no real image is formed. To an eye placed on the opposite side of the lens, the light now comes as though from an enlarged image at a greater distance from the lens than is the object; but because the light does

not really come from this place the *image is virtual.* In this manner, a virtual image is formed by a common magnifying glass, sometimes called a simple microscope (Fig. 295).

The relation between the principal focal length f of a convex lens, the distance of the object d_o, and the distance of the image d_i, is expressed by the following equation:

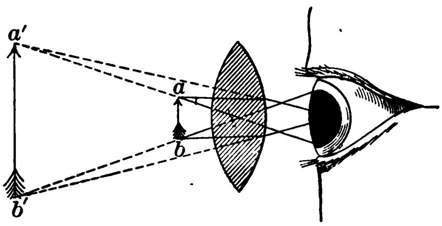


FIG. 295. — A virtual image $a'\,b'$ produced by a convex lens.

$$\frac{1}{f}=\frac{1}{d_i}+\frac{1}{d_o}.$$

Since image forming is simply the focusing of waves from points, this formula also expresses the relation between the principal and any two conjugate focal distances. Two of these three distances being known, we can find the third. When the principal focus or a conjugate focus is virtual, that is, when the image is virtual, f and d_i are to be considered negative. The relation between any linear dimensions, as diameters, of object and image (S_o and S_i) and their relative distances from the lens (D_o and D_i) can be determined from the following:

$$S_o : S_i :: D_o : D_i.$$

The Relation between the Principal Focal Length and any two Conjugate Focal Lengths of a Lens.

A demonstration of this relation, sufficiently exact for our purpose, follows: For a thin lens there is no appreciable error in representing the rays passing through the lens as if each were refracted once at a point on the line MN (Fig. 296) instead of at the surface of the lens where it really occurs. Let OF be the principal focal length of a lens. Let the two lines AB and $A'B'$ sustain to each other the relation of object and image, either of which may be regarded as the object.

Then from similar triangles $AB : A'B' = CO : C'O$; but since CO and $C'O$ are conjugate focal lengths which we may call d_1 and d_2,

$$AB : A'B' = d_1 : d_2.$$

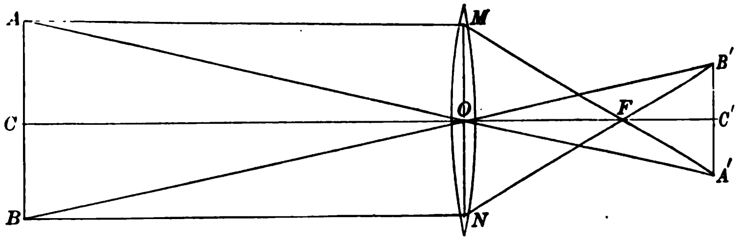


FIG. 296.

Also from similar triangles:

$$MN : A'B' = OF : FC'$$

but OF is the principal focal distance f, and $FC' = d_2 - f$.

Then $$MN : A'B' = f : (d_2 - f).$$

By construction $$AB = MN,$$

hence
$$\begin{aligned} AB : A'B' &= MN : A'B' \\ &= f : (d_2 - f) \\ &= d_1 : d_2. \end{aligned}$$

Consequently
$$\begin{aligned} d_1 : d_2 &= f : (d_2 - f) \\ d_1 (d_2 - f) &= d_2 f \\ d_1 d_2 &= d_2 f + d_1 f \end{aligned}$$

dividing by $d_1 d_2 f$ $$\frac{1}{f} = \frac{1}{d_1} + \frac{1}{d_2}.$$

207. The Action of a Concave Lens upon Light Waves. — Since a *concave* lens of any form is thinner along its axis than near the edges, that part of the wave which passes along the axis will be retarded less by the lens and will consequently gain on the remainder of the wave.

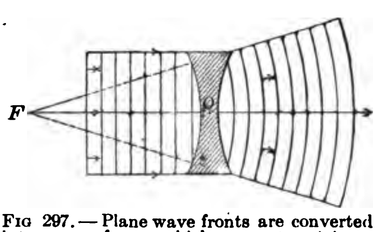


FIG 297. — Plane wave fronts are converted into convex fronts, which appear to originate at the virtual focus F.

The effect of this gain is shown in Figure 297, where a plane wave is thereby converted into a convex wave front. After passing out of the lens, though they do not come to a focus, the waves move as though they had issued from a luminous point F. This point F is, therefore, the principal ***virtual focus***

of the lens. Using the method of rays, these ideas are expressed by Figure 298. Evidently if a concave lens cannot bring plane waves, or parallel rays, to a focus, it would render more convex, or divergent, those which are already so. In a similar manner concave wave fronts (convergent rays) may be made less concave or even converted into convex fronts (divergent rays) by a concave lens as is shown in Figure 299. Because all the foci of a concave lens are virtual, this type of lens cannot form a real image.

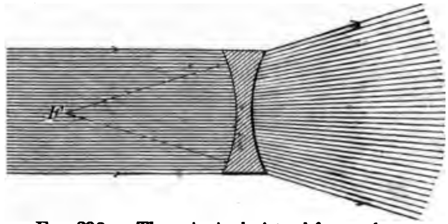


FIG. 298. — The principal virtual focus, shown by means of rays.

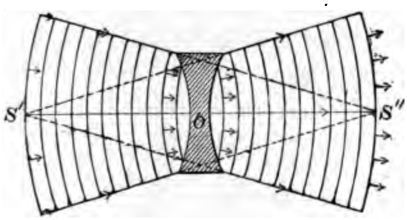


FIG. 299. — Concave wave fronts, convergent rays, converted into convex fronts, divergent rays, by means of a concave lens.

208. The Spherical Aberration of Lenses. — In our discussion of lenses we have assumed that a plane wave after passing through a convex spherical lens would be a truly spherical concave wave, hence, that all the light would come to a single point; or, expressed by the method of rays, we have assumed that parallel rays, after passing through the lens, would all meet at a common focus. This is not strictly correct, for those portions of the wave, or those rays which pass through the outer portions of the lens are more refracted than they should be to come to the true focus (Fig. 300). This failure of a spherical lens to bring to an exact focus all the light which originates at any one point, is known as *spherical aberration*. It is evident that spherical

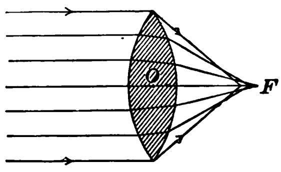


FIG. 300. — Spherical aberration.

aberration diminishes the distinctness of any image formed by a spherical lens. It may be entirely corrected by changing the shape of the lens so as to make the outer parts of the lens less refracting, or it may be partly corrected by cutting off the light from the outer parts of the lens by the use of a diaphragm (Fig. 301). The latter method is simple, but it also diminishes the amount of light getting through the lens, hence reduces the brightness of the image. Another common defect of a single lens is its production of colors in the image which do not exist in the object. This defect, together with the method of its correction, will be understood by reference to sections 209 and 210.

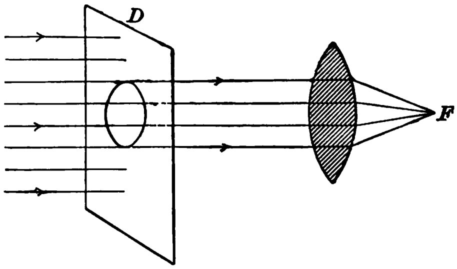


FIG. 301. — The diaphragm *D* cuts off the part of the light which is most refracted.

Questions and Problems

1. Make sectional drawings of the three varieties of each type of lens, and locate for each the principal focus and the principal axis.
2. Which type of lenses may form a real image? What seem to be the chief differences between an image formed with a lens and one formed through a pin hole?
3. A lens having a focal length of 12 cm. forms a real image of an object on a screen which is 20 cm. from the optical center of the lens. Find the distance of the object from the lens. Will object or image be larger? In what ratio?
4. A candle is 9 in. from a lens. If the lens produces a real image 54 in. from the candle, find the focal length of the lens.
5. An object is located at a point which is twice the principal focal distance from a lens. How does the size of the image compare with the size of the object?

209. The Dispersion of Light Waves. — A small band of direct sunlight when allowed to pass through a prism is not only refracted as a whole (sec. 200), but it is also separated into

a broader band, composed of various colors, as represented in Figure 302. This band of colors is called the *solar spectrum.* If light from any other source be similarly separated into its constituent colors, and thus be analyzed, the resulting color or colors is known as the *spectrum* of that source. To understand the color separation of light called *dispersion,* or the process by which the solar or any other spectrum is formed, it is necessary to recall the fact, that when the angle of incidence is the same, the amount of refraction produced by a given substance depends upon the wave length of the light. It can be shown that the greater the wave length, the less is the refraction. White light or sunlight consists of a mixture of practically all the wave lengths which affect the eye. Of these, the color red has the longest wave length, and the violet the shortest. The thin band of sunlight as it passes through the prism is therefore separated into slightly overlapping bands of color, corresponding to the different wave lengths present. The solar or any other spectrum shows the variety of wave lengths emitted by the particular source of the light. The dispersive power of a few important substances is given in the accompanying table:

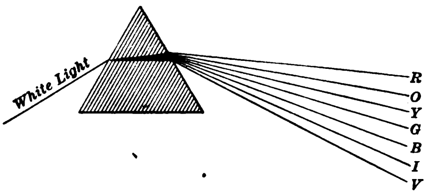


FIG. 302. — A prism separates white light into its constituent wave lengths and colors, which are arranged as shown. Red has the longest and violet the shortest wave length.

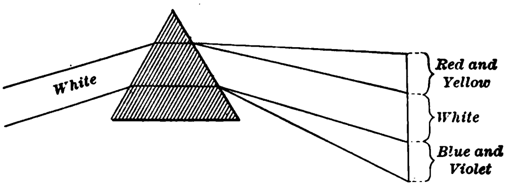


FIG. 303. — A broad band of light gives a spectrum with mixed colors.

Dispersion Power

Water	0.042	Crown Glass	0.043
Carbon bisulphide	0.145	Flint Glass	0.061

The length of the spectrum produced by these substances, other things being the same, varies as these dispersion powers. When the band of sunlight falling upon the prism is quite broad, the various colors or wave lengths may overlap upon the screen so widely that they again produce a mixture of all the colors, giving white light with only a red fringe at one end and a violet one at the other as shown in Figure 303. The rainbow is produced from white light by the dispersive action of drops of water in the air when the sun shines upon them at proper angles.

The Spectroscope. — Various instruments have been designed to make use of this dispersive power of a prism for the purpose of analyzing light; that is, separating light into its constituent wave lengths or colors. Such an instrument is called a spectroscope (Fig. 304). Since the particular wave lengths of the light emitted by a substance in a gaseous state depend upon the elements which constitute the gas, an analysis of the light emitted by it often serves to determine the composition of the body. The spectroscope is, therefore, especially valuable to the chemist and the astronomer.

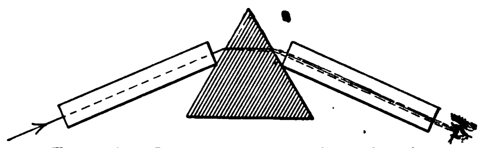


FIG. 304. — Showing the principle used in the spectroscope.

210. **Chromatic Aberration; the Achromatic Lens.** — It will be noticed when experimenting with spherical lenses that color effects are frequently apparent around the outer margin of the images. This is the result of the color dispersion, which has just been explained in connection with the prism. On light of mixed wave lengths, each part of a lens acts like a prism, separating the light into its wave-length constituents, as well as producing refraction. This dispersing effect is most noticeable at the outer parts of the lens where the angle of incidence is greatest, hence it is considerably diminished by using the stop,

or diaphragm, as suggested in connection with spherical aberration (Fig. 301). But complete correction can be produced only by using a combination of two lenses, one of which is concave and the other convex. By constructing them of different kinds of glass, for example, crown and flint, the dispersion of the convex lens may be neutralized by the concave lens without entirely destroying, though largely reducing, the amount of its refraction. Such a combination of two lenses is called an achromatic combination or lens (Fig. 305).

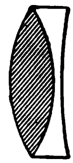


FIG. 305.—An achromatic lens. The convex lens is made of crown glass and the concave is made of flint glass.

211. The Compound Microscope. — The common magnifying glass, or simple microscope, has already been mentioned (Fig. 295, page 287). The compound microscope consists (1) of a convex lens of very short focal length, called the *objective*, which forms a real image of the object to be seen and (2) another

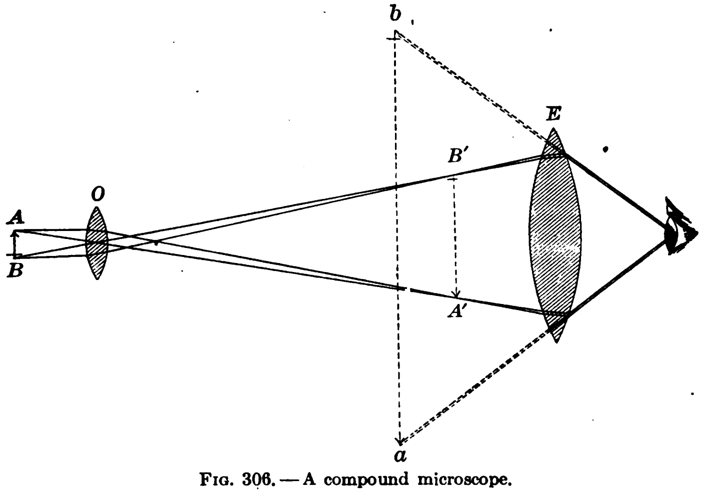


FIG. 306. — A compound microscope.

convex lens, *the eyepiece*, which is used to look at and magnify the image as the simple microscope does an object. By placing the object AB a very little farther from the objective O than the

principal focus (Fig. 306) there will be formed a much enlarged real image at $A'B'$. Upon viewing this image by means of a second lens, E the eyepiece, placed at less than its focal distance from $A'B'$, we get an enlarged virtual image ab. The length of ab divided by the length of AB is the magnifying power, or the number of diameters the microscope magnifies. When the magnifying power is high, the illumination must be very strong or the enlarged image will be very dim.

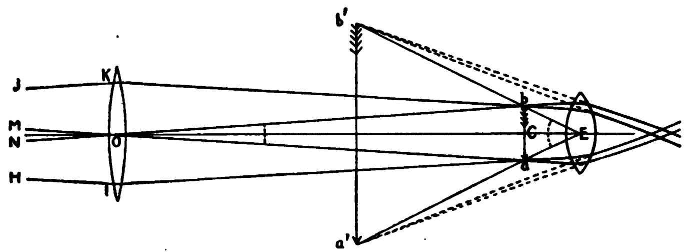


FIG. 307. — The astronomical telescope.

212. The Astronomical Telescope. — This instrument, except in size, differs little from the compound microscope. Being designed to look at distant objects only, the objective is large, so as to gather much light, and for convenience in construction its focal length is long. The real image formed by the objective KI (Fig. 307) is always very small compared to the distant object, hence the final virtual image, though magnified by the eyepiece, is generally very much smaller than the object viewed.

213. The Magic or Projection Lantern. — The chief parts of this instrument are (1) a powerful source of light to illuminate brightly the object, which is usually a more or less transparent plate called the slide, (2) a lens or more generally a pair of lenses to concentrate the light on the slide, and (3) the objective or achromatic convex lens which forms the real image of the slide on a distant screen (Fig. 308). This image, being much more distant from the lens than the slide,

is much enlarged. Because the lantern produces an inverted real image the slide must be put into the lantern in the inverted position in order to have it appear erect on the screen.

214. The Opera Glass or Galileo's Telescope. — The first telescope ever constructed (about 1609) was identical in principle with that used in the modern opera glass. It consists of a convex lens used as the objective and a concave or diverging lens as the eyepiece. The instrument is designed for distant or moderately distant objects. The concave lens is placed

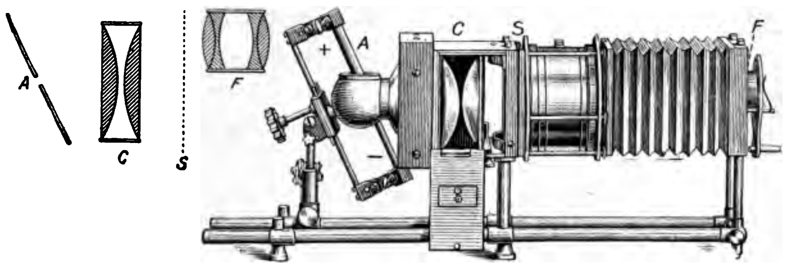


Fig. 308. — Projection lantern; (*A*) arc light; (*C*) condenser; (*S*) slide to be illuminated; (*F*) focusing lens.

nearer to the objective than is its principal focus. In the opera glass the concave lens, in this position, practically neutralizes the action of the convex lens of the eye, and the objective virtually produces the image on the retina of the observer. The common opera glass has a small field of vision and rarely magnifies over two or three diameters. Its strong points are found in its small length and in the fact that it does not produce inverted images as do the astronomical telescope and the microscope. Figure 309 shows how the image is produced. The convex lens *KI* would produce an inverted real image of a distant object at *ab*, but by placing the concave or diverging lens *E* nearer to the convex lens than is this image the light diverges after passing through *E*, and to an eye near *E* seems to come from *a'b'*, hence *a'b'* is the virtual image of the object.

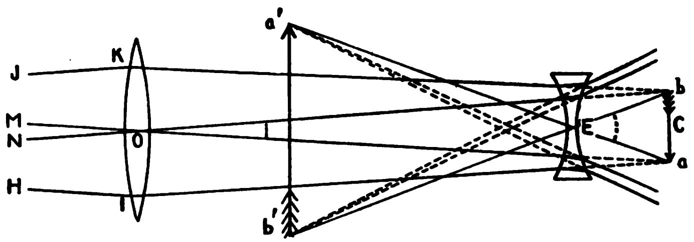


FIG. 309.

215. The Photographic Camera and the Eye. — The common camera consists of a convex lens arranged at one end of a box, which is closed to shut out other light, so that the lens may form a distinct, real image on a plate or film placed at the other end of the box. In order to secure an accurate image it is frequently necessary to "focus" the camera, that is, it is necessary to move the lens or the plate, until object and image are in the position of conjugate foci (sec. 205). The manner of formation of the image is simply that already shown for a convex lens (sec. 206).

A study of the structure of the eye or of the manner in which seeing is effected physiologically, does not properly belong to a course in physics. As an optical instrument the eye is much like the photographic camera, there being a convex lens and a sensitive screen, the retina, upon which the image is formed. Accommodation or focusing, because the retina cannot be moved at will, is accomplished by a change in the curvature, and hence of the thickness and refractive power of the crystalline lens (Fig. 310).

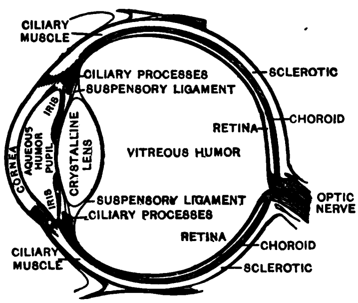


FIG. 310.—The human eye.

216. Some Optical Defects of the Eye and their Correction. —

The most important defects of vision are known as short sight, long sight, and astigmatism.

Short sight is the result of the eye being so long from front to back that the lens brings the rays of distant objects (Fig. 311) to a focus before they reach the retina, hence only very near objects with highly divergent rays can be distinctly focused on the retina. This defect is remedied by using a concave lens, which gives more divergence to the rays, so that those from distant objects no longer come to a focus before they reach the retina.

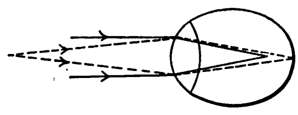


FIG. 311.—Short or near sight. Only the highly divergent rays of near objects come to a focus on the retina.

Long sight is due to a condition opposite to that of short sight—the eyeball being too short. The rays from all except distant objects are so divergent that the crystalline lens cannot bring them to a focus before they reach the retina, even when the lens is as thick as the power of accommodation can make it (Fig. 312). This defect, common in older people, can be remedied by the use of a convex lens, which assists the lens of the eye to focus the very divergent rays of near objects.

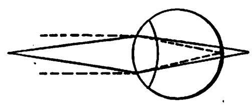


FIG. 312.—Far or long sight. Only the nearly parallel rays of distant objects come to a focus on the retina.

Astigmatism. — The normal eye is symmetrical or nearly so about its axis, so that all sections through the eye along the axis are equally curved. Hence the eye is able to see vertical and horizontal lines distinctly at the same time. But some eyes are unable to see with equal distinctness lines arranged as shown in Figure 313, a particular set being decidedly more sharply defined than the

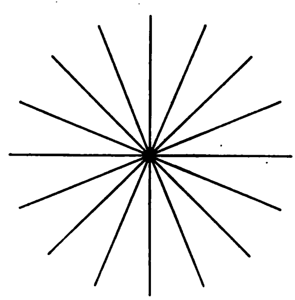


FIG. 313.—To an astigmatic eye some of the lines seem more distinct than others.

others. This defect is called *astigmatism.* It may be remedied by the use of a cylindrical lens the curvature of which makes up for the lack of curvature in the eye.

217. **Color.** — It has already been noted that when a thin band of white light is passed through a prism the various wave lengths of which it is composed are separated, thus forming the spectrum. This band of light, arranged according to the relative wave lengths, appears to the normal eye as a band of colors each blending into its neighboring colors. Plainly, then, *color is a sensation* which depends upon the wave length of the light which enters the eye. In discussing the nature of the sensation of sound we discovered that the character of the effect produced upon the ear depends upon the vibration frequencies, or wave lengths, and the relative intensities of the various tones which produce the sensation. The fundamental characteristic of a sound sensation, called its *pitch,* depends directly upon the frequency or wave length of the sound waves. Similarly, the fundamental characteristic of a light sensation, called *color,* depends directly upon the frequency or wave length of the light waves. The eye, however, is much less able to distinguish the different constituents of a set of mixed light waves than is the ear to distinguish sound waves. While the sensation white may be produced by a combination, with proper intensity, of all the visible wave lengths, white may also be produced by a combination of two, three, or more, properly chosen distinct sets of wave lengths. In a similar way any distinct color sensation produced by one wave length may also be produced by a combination of two or more distinct sets of wave lengths. This is frequently stated thus: any distinct color may be produced by a combination of two or more colors. (It must be noted that color as here used does not mean paint or pigment.) The exact nature of a color effect depends upon three things: (1) the vibration frequency or wave length of the light, sometimes called the *hue* of the light, (2) the brightness or intensity, and (3) to

what extent the light under consideration is mixed with white light. When free from white light the color is said to be pure.

218. The Young-Helmholtz Color Theory. — The most acceptable theory of color sensation is the one first proposed by Thomas Young and subsequently extended by Von Helmholtz. Since any color sensation can be produced by the combined action, in suitable proportions of three given sets of wave length, namely, those which separately produce red, green, and blue, this theory asserts that the eye is provided with three sets of nerves — one set, when stimulated, furnishing the sensation of red, another that of green, and the third that of blue (or violet). A normal stimulation of all three sets of nerves produces the sensation of white. Generally speaking, no one set of nerves is stimulated *exclusively* by any one kind of wave length, but only *chiefly* by one kind; thus red wave lengths stimulate chiefly the nerves of the red color sensation, but also those of green and blue to a less extent. In a similar manner green and blue wave lengths each stimulate somewhat the other two sets of color nerves. A color-blind person is one in whose eyes one set (rarely two sets) of nerves is either lacking or for some reason fails to respond to the action of the waves.

219. Complementary Colors. — We have already called attention to the fact that the sensation of white can be produced by a number of combinations of colors in sets of two each. Any two colors which combined produce the sensation of white are said to be complementary. Any single color viewed for a long time becomes tiresome. But complementary colors, since they furnish an approximately even and general stimulus to the color sensations, are agreeable to the eye.

220. The Color of Objects. — *Color*, as has just been shown, is a term which properly applies indirectly to a sensation and directly to the character of the light which produces it. Commonly we speak of objects as having color in much the same way that we speak of musical strings and organ pipes as having

pitch, though we know that pitch is a characteristic of the sound produced and not of these bodies. In both cases we refer the quality of the effect back to the object sending the waves. The so-called color of an object is, more correctly speaking, the color of the light which comes from the object to the eye.

The color of luminous bodies depends entirely upon the kind of light they are emitting or generating. Thus the carbon wire in a glow lamp may be first a dull red, then orange, yellow, etc., until finally it is approximately white, as the current through the lamp grows stronger.

The color of non-luminous bodies depends upon the kind of light they receive and how they treat it. A perfectly transparent body would be invisible and colorless. A piece of thin plate glass is one of the nearest approximations to such a substance in the solid form. It is almost impossible to tell by sight alone whether a bottle is empty or entirely filled with pure water, or alcohol. Many transparent bodies are not equally transparent to all wave lengths, hence the light which they transmit is likely to be different in color from that which enters them. Each kind of glass is said to have the color of the light which it transmits in greatest amount when white light strikes upon it. Besides depending upon the kind of light received, the color of a transparent body also depends upon the kind of light it transmits. For example, a piece of red glass is able to transmit red light and little more; the rest of the white light is absorbed. We all know that to get the full effect of a stained glass window the observer must be on the side of the window opposite to that of the stronger light.

Color of Opaque Bodies. — When white light falls upon paints or pigments, the waves penetrate a certain distance and are then reflected out again. Hence the color of the paint is due to the kind of light which is not absorbed. Thus yellow paint absorbs all but the yellow and a part of the neighboring colors in the spectrum, green and orange, while blue paint absorbs all but the blue and

the neighboring colors, green and violet. A mixture of these paints will therefore absorb all but the green, hence the color of a mixture of yellow and blue paints is green. But the mixing of yellow and blue spectrum colors produces gray or white. On this account the mixing of paints or pigments of given colors must not be regarded as the mixing of the colors represented by each alone. The mixing of paints produces the color or colors not absorbed by any of the constituents. The color of most opaque bodies originates in a manner similar to that of a paint. A few substances, such as gold, copper, and analine dyes, directly reflect certain colors, in addition to ordinary reflection, and admit the others. Thus gold is yellow by reflection, but green by transmitted light, though, unless the gold is very thin, the admitted light is all absorbed. Since they together produce white, the color of the admitted light is complementary to that which is reflected. Objects which completely admit and absorb sunlight, that is, light of practically all kinds of wave length, are said to be black. Pure black simply means that the object sends no light to the eye, hence, strictly speaking, black is not a color.

221. **The Relation of Light to Radiant Heat and other Radiant Energy.** — The luminiferous ether is the medium for waves of widely different wave lengths. The longest of those which affect the eye are about .00008 cm. in length and the shortest about .00004 cm. The form of energy known as radiant heat (see section 146) is transmitted by ether waves which exceed .00008 cm. in wave length. Other ether waves have been determined, some of which, having wave lengths shorter than those of light, are most active in photographic processes, and others having wave lengths longer than those of radiant heat, constitute the waves of "wireless" telegraphy. All these ether waves travel with the speed of light and in general they obey the laws of reflection and refraction as given for light. (See sections 195 and 200.)

Questions and Problems

1. Is color a characteristic of objects or of a sensation dependent upon the kind of light which enters the eye?

2. What is the fundamental difference between red and yellow, or between any other two lights of different color?

3. What does a prism prove concerning the nature of white light? May the sensation of white or gray be produced in any other way? Give an example.

4. State the objection to calling black a color. Does the objection apply to white?

5. The difference in light waves which produces a difference in color, when applied to sound waves would produce what difference?

6. The color of an object depends upon what two things?

XIV. MAGNETISM

222. The Natural Magnet or Loadstone. — A certain mineral, found originally near Magnesia in Asia Minor, is able to attract and hold continuously small particles of iron. This mineral, composed of iron and oxygen, is called a natural magnet or loadstone. Its chief interest is historical.

223. Artificial Magnets. — By processes explained in sections 229 and 262, pieces of hard steel, such as files and needles, can be readily converted into magnets far superior to natural magnets both in strength and in convenience of shape. These, known as *artificial* magnets, are exclusively used in all magnetic investigations and applications.

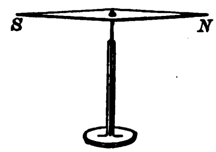


FIG. 314. — Pivoted magnetic needle.

224. The Poles of a Magnet. — If a bar of magnetized steel is balanced on a point as shown in Figure 314, or is suspended by a thread without twist, it will come to rest with one of its ends pointing north and the other south. When rolled in a quantity

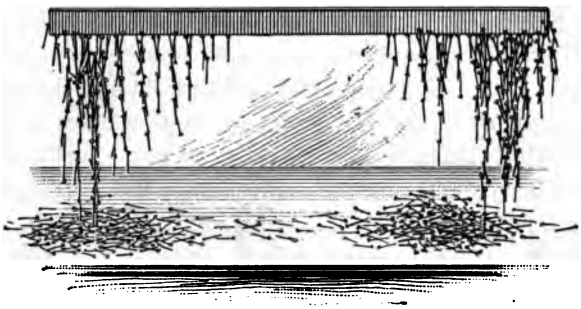


FIG. 315. — Showing the poles of a bar magnet.

of iron filings or small tacks, the iron clings to the magnet in great quantities at and near the two ends (Fig. 315). These

ends or places where the magnetic attraction is greatest are called the poles of the magnet. *That pole of the suspended magnet which points northward is called the north-seeking or north pole, and the one pointing southward the south-seeking or south pole.* The fact that these ends are not interchangeable, that is, that a suspended magnet is not in stable equilibrium if turned through 180°, shows that the poles are different in their nature.

225. Action of Magnets upon Each Other. — Having found and marked the north and south poles of two magnets, we can then find the action of magnetic poles upon each other by holding one magnet in the hand and slowly bringing each of its poles in turn toward each of the poles of a freely suspended magnet. The results plainly show that *a north pole repels another north pole,* and *a south pole repels another south pole,* but *a south and a north pole attract each other. Briefly, like magnetic poles repel and unlike poles attract each other.* The amount of this attraction or repulsion depends upon the strength of the two poles, and also varies inversely as the square of the distance between them. A pole of *unit magnetic strength* is a pole of such strength that when placed in a vacuum 1 cm. from an exactly equal pole repels it with the force of 1 dyne.

226. Action of Magnets upon other Bodies. — Magnets attract all the varieties of iron — soft or wrought iron, cast iron, and steel. They also attract nickel and cobalt, though much less strongly than they do iron, and a few other substances very slightly. Magnets slightly repel all other bodies, but this repulsion is so small that generally it may be neglected.

Though most bodies are not attracted by a magnet, they do not cut off magnetic action, that is, when they are placed between a magnet and a piece of iron they do not prevent the magnet from attracting the iron. But the interposed bodies necessarily keep the magnet and iron farther apart, hence, they diminish the amount of the attraction between them.

227. Magnetic Induction. — When a magnet is brought near to a piece of unmagnetized iron, as shown in Figure 316, the iron becomes magnetized by the action of the original magnet. The north and south poles of this new magnet point respectively in the same directions as those of the original magnet, and they grow in strength as the magnet and iron are brought nearer to each other.

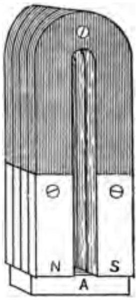
FIG. 316. — Magnetic induction; the end A of the iron bar becomes a south pole.

Whenever a magnet produces a magnetic condition in a piece of iron placed near it, the process is called *magnetic induction.* As a result of magnetic induction there is always produced, next to a given pole of the original, an opposite pole in the new or induced magnet. In consequence we can easily see why a magnet always attracts unmagnetized iron. As any piece of iron approaches a magnet it becomes magnetized by induction, thus bringing the opposite or attracting poles of the old and new magnets next to each other. A second and third piece of iron placed in contact with or near to the first will also experience induction in a manner similar to the first, but in a less degree. This explains why the iron filings or tacks arrange themselves in rows as shown in Figure 315.

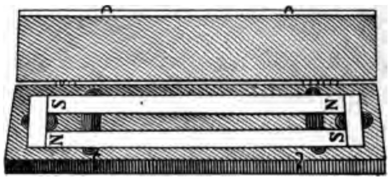
228. Temporary and Permanent Magnets. Retentivity. — If the iron used in demonstrating the induction (Fig. 316) is of the purest or softest kind, it will lose practically all of its magnetism upon being removed from the original magnet. Hence we say that the *retentivity* of soft iron is very small. If the hardest variety of iron is used, for example a steel file, though the induction takes place less readily, the steel when removed retains nearly all the magnetism which it had while in contact with the original magnet. That is, the retentivity of the hardest steel is the highest known. On account of this difference in retentivity a magnet produced by the use of

soft iron is called a *temporary* magnet, and that by the use of steel a *permanent* magnet. These terms are not to be taken in the absolute sense. Rarely if ever does a piece of soft iron when once magnetized lose all trace of it, and likewise no piece of steel would retain all the magnetism which it is able to receive. At a high temperature, about 700° C., all magnetism disappears from steel magnets. Blows and rough handling likewise frequently injure good permanent magnets.

229. How to produce Good Magnets. — Since the original magnet does not lose its magnetism by inducing or setting up the magnetic condition in other bodies, we may produce, by induction, any number of magnets, temporary or permanent, provided we have a fairly good original magnet, and the pieces of iron and steel to be magnetized. The iron or steel to be magnetized may be any desired shape, but either straight or horseshoe-shaped bars are most commonly used. One advantage of the horseshoe form is that both of its poles may be used to attract the same bar of iron (Fig. 317). A needle, small file, or other bar of steel can be readily magnetized by drawing either pole of the original magnet along the entire length of the needle a few times, always in the same direction, taking care to keep the needle and magnet a considerable distance apart while returning for the next stroke. Since this is an inductive process, the end of the needle last touched will have the opposite polarity to the one touching it. It must be understood that the reason for moving the magnetic pole along the steel bar is to make the magnetic induction stronger by bringing the pole as near as



Horseshoe magnet with soft iron armature *A*.



Bar magnets with armatures.

FIG. 317.

possible to each of the particles of the steel. Friction does not produce the result, hence hard rubbing is of no advantage. Not only can an unmagnetized needle be magnetized by this application of magnetic induction, but one already magnetized may have its poles reversed by the similar action of a stronger magnet. On this account care is required when strong magnets are suddenly brought near small magnets with marked poles, such as those used in compasses, for a too rapid approach will sometimes reverse the magnetism of the needle before it has time to turn and present the proper pole. This may subsequently produce confusion in the identification of the poles. Another and, especially when large magnets are needed, a better method of producing magnets will be shown in section 262, where the electric current is used.

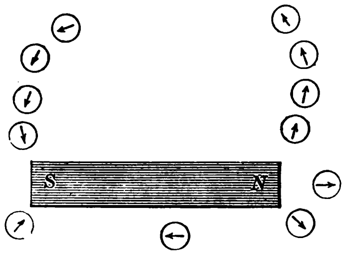


FIG. 318. — The directions of the lines of magnetic force are shown by means of a small compass.

230. Field of a Magnet; Lines of Magnetic Force. — If a small magnet, such as a pocket compass, is placed in different positions around either pole of a bar magnet as shown in Figure 318, the north end of the needle will point in different directions in different positions. Similarly, when a bar magnet is placed beneath a sheet of stiff paper and iron filings are scattered slowly upon the paper they arrange themselves in curved lines, as shown in Figure 319. Each particle of iron, being an induced magnet, acts like a

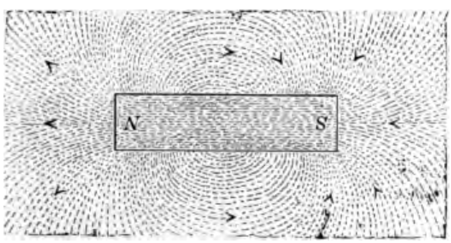


FIG. 319. — A horizontal section through the magnetic field of a magnet. The directions of the lines of force are indicated by arrow heads.

small compass needle. Again if a small magnet, suspended by a silk fiber, is placed anywhere in the air around a magnet it assumes a particular direction for each position (Fig. 320). These facts show that there is a magnetic action in all directions and at considerable distances from the poles of a magnet. The space around a magnet, in which its magnetic action is noticeable, is called the *magnetic field.* The intensity of the magnetic action at any point in a field is known as the *magnetic force.* The lines along which the filings or other small magnets arrange themselves are called the *lines of magnetic force.* The *direction of a line of magnetic force* is the direction indicated approximately by the north pole of a very small magnet placed at any point on that line, or ideally it is the direction in which a free north pole would move if placed there.

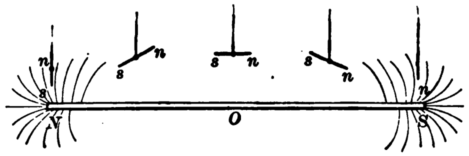


FIG. 320. — A suspended magnet shows the direction of the lines of force above the magnet *O*.

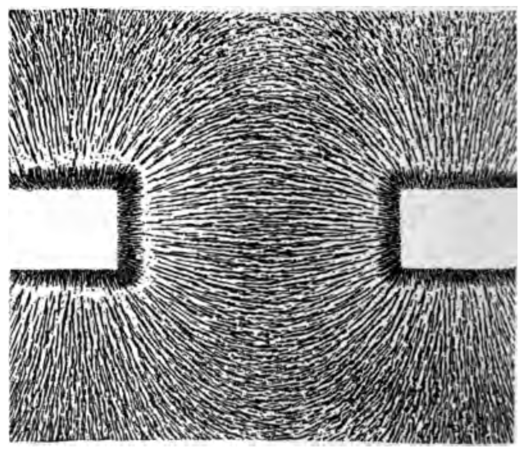


FIG. 321. — Two unlike poles.

Intensity of the field. — If the magnetic strength at any point of a field is such that a unit pole (sec. 225) placed there will be acted upon with the force of 1 dyne, the field has *unit intensity*, and we may agree to draw or imagine one line of magnetic force for each

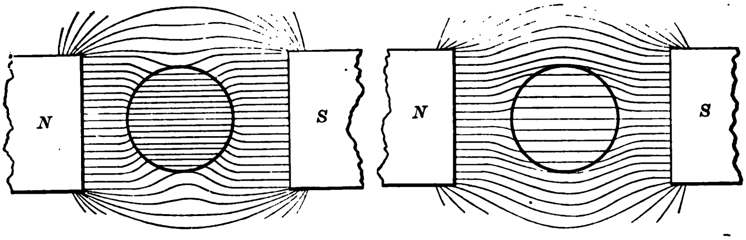


FIG. 322.—Effect of introducing in a uniform magnetic field; (1) a sphere of magnetic substance; (2) a sphere of a nonmagnetic substance.

square centimeter in such a field at right angles to the direction of the lines of force. The relative intensities of any two different magnetic fields or the relative intensities of different parts of the same field may be represented by the number of lines of force per square centimeter, taken perpendicularly to those lines. When a north pole of one magnet is placed near the south pole of another, the lines of force seem to attract each other and the field of force between them becomes much stronger than when either pole is there alone (Fig. 321). Since the lines of force run through iron better than through air or other substances, iron is said to be more *permeable* than any other substance. Hence, the field between two opposite poles is also made stronger or more concentrated by the

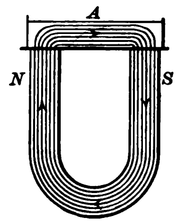


FIG. 323.—A magnetic circuit showing the lines of force in the horseshoe magnet and the soft iron armature *A*.

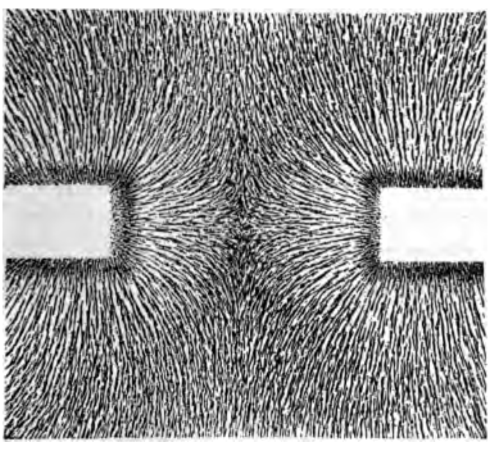


FIG. 324—Two similar poles.

presence of iron instead of air in the space between them (Figs. 322 and 323). When the two poles are of the same kind, the lines of force between them, instead of being concentrated as with opposite poles, diverge as shown in Figure 324.

231. Information gained by breaking a Magnet. — A bar of steel, such as a long needle, when carefully magnetized, shows polarity at or near the ends only. When broken anywhere both pieces show poles, one a north and the other a south, at the place of breaking where none were noticed before. This breaking can be continued indefinitely, each new piece being a complete magnet with two opposite poles as shown in Figure 325. This fact has led to the belief that each molecule is a

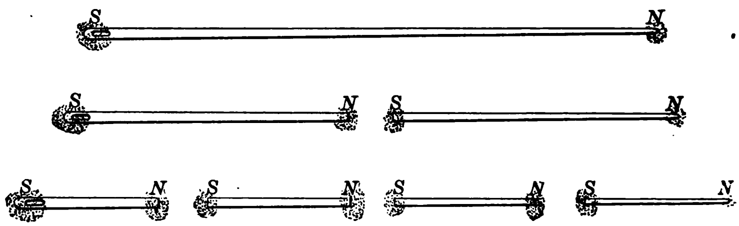
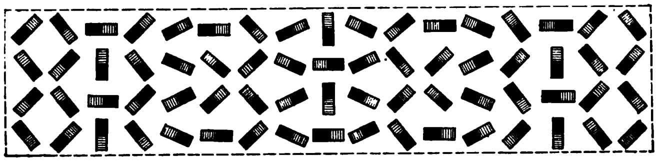


FIG. 325. — The magnetic poles make their appearance in pairs wherever the magnet is broken.

magnet, the poles of which point in the same general direction as those of the magnet as a whole. Before breaking all the adjacent poles neutralize each other, hence, all are neutralized excepting those at or near the ends of the magnet. Breaking does not create, but simply reveals the poles which already exist. Joining the broken pieces, because we cannot get them quite so close as they were, only approximately neutralizes again the poles at the joints. It is further believed that all the molecules in a magnetic substance, like iron, are always little magnets, each having a north and a south pole. In an unmagnetized piece of soft iron or steel these molecular magnets are so arranged that their poles neutralize each other (A, Fig. 326). Under the influence of magnetic induction the molecules are turned, those

of soft iron easily, those of steel with difficulty, until all poles of one kind point approximately in one direction; then the body as a whole is magnetized (*B*, Fig. 326). It must not be assumed from the figures that we know anything about the actual shape of the molecules. Since soft iron loses its magnetism so easily, its molecules must swing out of position

A



B

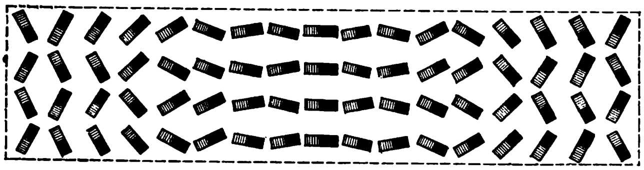


FIG. 326.—Probable arrangement of molecules in an unmagnetized iron bar (*A*) and in a magnetized iron bar (*B*).

just as readily as they swing into it. The molecules of steel, on the other hand, are as slow to get out of line as they are to get into it, thus explaining the difference between a temporary and a permanent magnet. These views of magnetism find strong support in many facts; for example, a glass tube filled with iron filings may be magnetized by induction and the tube as a whole has north and south poles. Tapping the filings facilitates the production of the magnetism while the inducing magnet is present, and also facilitates the loss of the magnetism when the inducing magnet is removed.

232. Magnetic Action of the Earth. — Attention has already been directed to the fact that a freely suspended magnet always points in approximately the same direction after it comes to rest. Magnets delicately balanced on a point so that they

may rotate in a horizontal plane, are largely used to determine directions on land and sea, under the names of *surveyor's* and *mariner's compass.* Pieces of unmagnetized steel can be magnetized by being held in the proper position and tapped with a hammer, thus showing the inductive action of the earth. Since these effects may be observed anywhere, we must conclude that around the earth there is a magnetic field much the same as there is around an artificial magnet.

FIG. 327. — A magnetic needle suspended free to turn in any direction.

233. The Dipping Needle. — If a long piece of steel is suspended as nearly as possible at its center of gravity, leaving it free to move in approximately all directions, and then magnetized, the north pole of the needle will point northward but at the same time downward. The line connecting the two poles of the needle makes an angle (about 70° at New York) with the horizontal plane, and the needle is said to *dip* (Fig. 327). In a better method of construction the steel bar is first carefully balanced on horizontal and vertical axes so that it will remain in any position in which it may be stopped, and then it is magnetized. A magnet so mounted, known as a *dipping needle,* is able to show the true direction of the lines of force in the earth's magnetic field (Fig. 328). In the southern hemisphere the south-pointing end of the needle dips or points downward.

FIG. 328. — A dipping needle.

234. The Direction of the Earth's Magnetic Field; the Earth's Magnetic Poles. — By means of the compass and the

dipping needle, maps of the magnetic lines of the earth have been made. These magnetic surveys, as they are called, have been extended over the greater part of the earth, and are of much value to surveyors, mariners, and to investigators generally. For reasons not yet definitely known, the earth's magnetic field is undergoing constant changes, which, however, are small for any one year.

Magnetic surveys also show that the earth has two (possibly more) magnetic poles neither of which agrees in position with the earth's geographic poles. The magnetic north pole is probably more than 1000 miles from the earth's geographic north pole, at a point, within the earth, somewhere to the north of British America (Fig. 329). Little is known of the location of the magnetic south pole. Because opposite poles attract, it follows that the north magnetic pole of the earth has the same polarity as the south pole of a magnetic needle, or the earth's north pole is opposite in polarity to that pole which we call the north pole of a magnet.

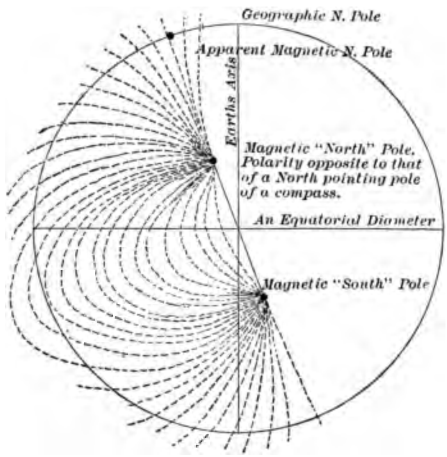


FIG. 329. — An ideal section through the earth taken approximately along the agonic line. It shows the approximate directions of the lines of force in the earth's magnetic field.

235. Magnetic Declination; Line of no Variation. — Because the earth's magnetic and geographic poles do not agree in position, the compass at most places on the earth's surface points somewhat to the east or west of the true or geographic north. The amount of variation from the true north is called

the *declination* of the needle at that place. At New York in 1900 the declination was about 9° west of the true north. At all points on an irregular line running (in 1900) through central Michigan, western Ohio, eastern Kentucky, western North Carolina, and central South Carolina, the needle points to the true north. This line is known as the *agonic line* or line of no variation. It is an interesting as well as important fact that the agonic line is slowly shifting its position westward. At all places in the United States east of the agonic line the compass points west of, and at points west of this line it points east of the true north. The amount of the declination at any place can be roughly determined from the map shown in Figure 330. The accompanying table shows the changes which have occurred in the declination at some important centers during the nineteenth century:

	1800	1850	1900
New York	4°.3 W.	6°.3 W.	9°.1 W.
Washington, D.C.	0°.2 W.	1°.8 W.	4°.6 W.
Chicago	.	6°.0 E.	3°.3 E.
San Francisco	13°.6 E.	15°.8 E.	16°.6 E.
Sitka, Alaska	26°.4 E.	29°.0	27°.9 E.

Questions and Problems

1. Draw the lines of force between two unlike magnetic poles, (*a*) when there is air between them, (*b*) when there is a bar of iron connecting them, and (*c*) when there is an iron ring in the field between them.
2. From its effect on the field, explain why an iron keeper or armature is used to preserve the strength of a horseshoe magnet.
3. From your understanding of magnetic induction, explain why a piece of soft iron is attracted by either magnetic pole.
4. Does the compass or the dipping needle show the true direction of the earth's magnetic field? Does the position of the axis of the dipping needle affect its dip? Explain.
5. Draw the magnetic field between two similar poles placed near each other. When do the lines of force from two poles blend?
6. A magnetic pole of 8 units' strength is placed 6 cm. from another similar pole of 24 units' strength. Find the number of dynes with which one acts upon the other. Is the action attraction, or repulsion?

LINES OF EQUAL DECLINATION FOR THE YEAR 1900.

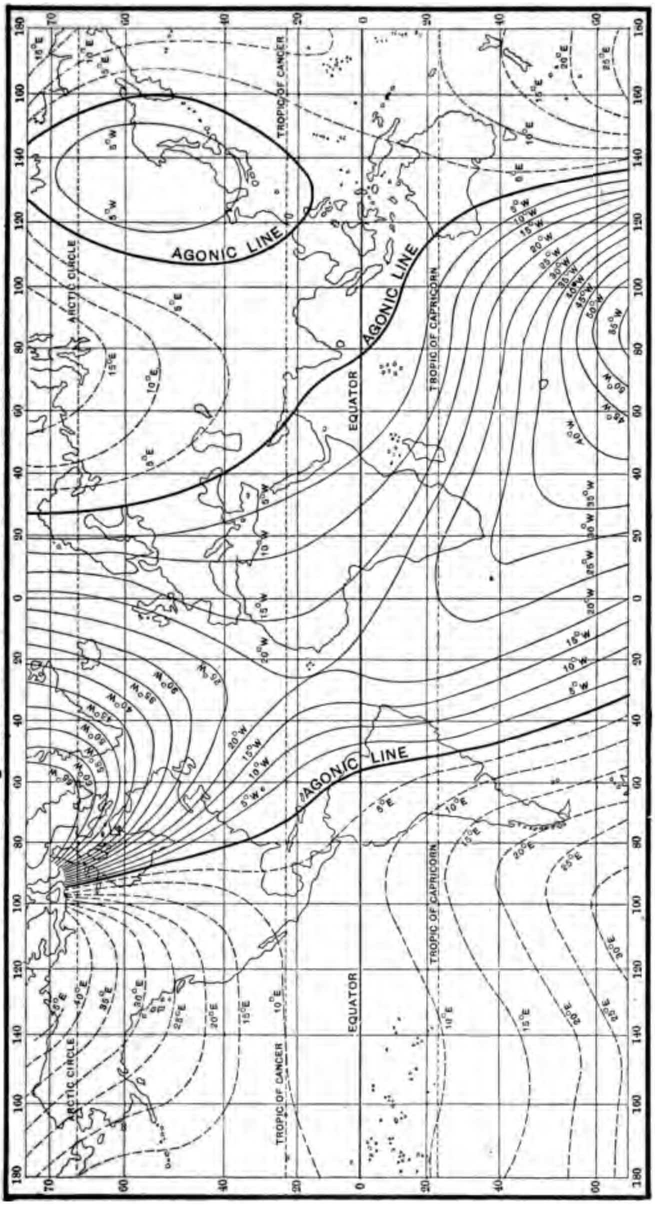


FIG. 330.

XV. ELECTROSTATICS

236. Electrification; how Produced. — A glass rod when rubbed with a piece of dry silk will acquire the ability to attract to itself bits of paper, threads, and other bodies, many of which are repelled or fly away after touching the glass. If the bare hand is rubbed along that part of the glass which was rubbed with silk, the rod loses its ability to attract the light objects. Plainly this attraction is not gravitation, for a simple test shows it did not exist previous to the rubbing. It is not magnetic attraction, (1) because the glass and paper are not magnetic substances, (2) because a magnet may be touched with the bare hand in any manner without any loss in its magnetism, and (3) because it gives to a body no disposition to point north and south. Since this attraction is different from any that we have studied up to this time, it requires, on that account, a different name. Because it was first observed, by the ancient Greeks, in a substance called *electron* (amber) it was given the name *electrical* attraction. A body manifesting this electrical attraction, or repulsion, is said to be in a *state of electrification* or to have a *charge of electricity.*

Not only does the rubbing of glass and silk produce electrification, but the rubbing together of sealing wax and flannel, hard rubber and fur, or sulphur and flannel also produces it; indeed, with proper precautions, we may develop electrification by the use of *any two different substances.* The rubbing serves merely to bring in contact as many points of the two bodies as possible. The energy of the charge is of the potential type and it is due to the work which the experimenter does when he separates the two bodies.

237. Concerning the Nature of Electricity. — At this point the beginner usually is eager for an answer to the question, "What is Electricity?" or "What causes Electrification?" He frequently thinks that he cannot go on with his study and make satisfactory progress without knowing. Probably the best answer to this question is the frank admission that we do not know the *exact nature* of that which we call *electricity.* But it is also true we do not know the exact nature of that which is called the *life* of a plant or an animal. A failure to define life in no serious way hinders our successful study of the *characteristics* and *activities* of living things as they are revealed in elementary botany and zoölogy. Likewise a successful study of the conduct of various bodies when they are affected by electricity can be carried on without knowing what electricity is. But should we ever become fully prepared to give answers to these questions, and the world seems to be making progress in that direction, these answers would, of necessity, come well toward the end of our studies, rather than at the beginning of them.

238. Kinds of Electrification. — If one end of a glass rod, suspended in a paper sling as shown in Figure 331, is rubbed with silk, we find that there is repulsion between this electrified end of the rod and another similarly electrified glass rod held near it. But the unelectrified end of the suspended rod is attracted by the electrified rod, just as the unelectrified bits of paper are attracted. If a piece of hard rubber or vulcanite is electrified by rubbing it with fur and it is then alternately held near the two ends of the suspended glass rod, we find that the vulcanite attracts both ends, the electrified as well as the unelectrified ends. The difference in

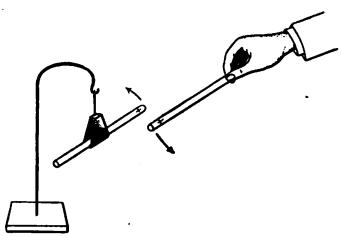


FIG. 331 — The electrified glass rods repel each other.

the conduct of these bodies toward the electrified end of the suspended rod leads to the conclusion that there are two kinds of electrification — the kind produced on the glass and the kind produced on the vulcanite. *The kind produced on glass when rubbed with silk is called positive* (+) *and the kind produced on vulcanite when rubbed with fur is known as negative* (−) *electrification.* By careful experimentation we can show that in the cases mentioned above the silk and the fur were electrified as well as the glass and rubber, the silk being negatively and the rubber positively electrified. Indeed, in every case where one kind of electrification is produced, the other kind is also produced, though with some substances it is more difficult to detect the electrification than with others.

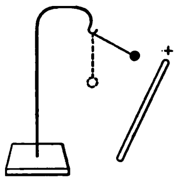


FIG. 332. — The unelectrified ball is attracted by the electrified glass.

Hereafter, we shall generally refer to glass and silk, when rubbed together, as furnishing the standards of *positive* and *negative* electrification, respectively. The terms positive and negative as here used must not be assumed to mean that one of these kinds of electrification is more real or active than the other, but simply that in certain respects they are opposite. That the kind of electrification on the glass when rubbed with silk was called positive rather than negative is, in a sense, a mere accident. The names could have been reversed in the beginning of the science of electricity without any disadvantage.

239. Action of Electrified Bodies upon Each Other; Unit Charge. — Attention has been called to the fact that two glass rods, when similarly electrified, repel each other. A small *pith ball* or cork suspended by a silk thread is readily attracted by an electrified glass rod (Fig. 332). After touching the glass it is, generally, repelled (Fig. 333). This leads to the conclusion that the pith ball in the act of

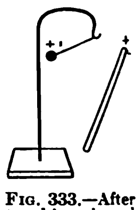


FIG. 333.—After touching, the rod and the ball repel each other.

touching must receive a share of the positive charge of the glass rod, and is, on that account, repelled. The ball may then be discharged, by taking it in the hand (see conduction), and if the electrified vulcanite is now brought near to it, attraction is noticed at first, but again after contact repulsion follows. This time the ball receives a share of the negative charge of the vulcanite. The positively electrified glass rod held near it will now vigorously attract the negatively electrified ball, just as the negatively electrified vulcanite attracted the positively electrified glass in the case previously described. From all these facts we conclude (1) that either a positively or a negatively electrified body attracts an unelectrified body brought near to it, (2) that bodies similarly electrified repel each other, (3) that bodies oppositely electrified attract each other. Further investigation has shown (4) that the amount of the attraction or repulsion varies directly as the product of the two charges and inversely as the square of the distance between them.

A unit of electrification or *unit charge* is that charge or quantity of electricity which in air at a distance of 1 cm. from an exactly equal charge repels it with a force of 1 dyne.

240. Conductors and Nonconductors; Insulators. — A charge of either kind given to one end of an iron rod supported by a glass jar (Fig. 334) will quickly travel or spread itself over the entire rod, but when a charge is given to a glass rod it will remain practically at or near the point to which it was originally given. Those substances which, like the iron, readily transfer electrification or charges are known as *conductors;* and those substances which, like glass, do not thus transfer it are called *nonconductors* or *insulators.* It is on account of this difference between the glass and the iron that a glass rod may be electrified while it is held in the bare hand,

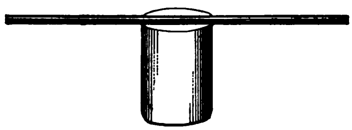


FIG. 334.—The metal conductor is insulated by means of the non-conducting glass jar.

but an iron rod cannot be electrified when thus held. Metals, carbon, and the solutions of salts in water are the best conductors; glass, silk, mica, hard rubber, sealing wax, porcelain, shellac, and paraffin are the best insulators. Many substances, for example, the human body and water, stand between these two extremes, and may be spoken of as conductors or nonconductors according to the conditions under which they are being used. A change of temperature often produces a decided change in the ability of a substance to conduct. Though there is a vast difference between the best and the worst conductor, there is no perfect conductor nor any perfect insulator. Since water is not a good insulator, there is need of great care in keeping everything *dry* when the very best insulation is desired, as is the case in many experiments.

241. The Electroscope. — In the experiments already discussed it was found that the small pith ball (Fig. 332) would serve to tell us whether the bodies we were using were electrified. If the ball is first charged with a known kind of electrification, for example by means of the glass rod which has been rubbed with silk, we may bring near to the ball any body, which is supposed to be charged, and by the observed attraction or repulsion determine the kind of the unknown charge. When thus used, the pith ball serves to determine (1) the presence of electrification and (2) its kind. Any instrument which serves either of these two purposes is called an *electroscope.*

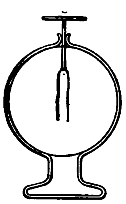


FIG. 335. — A gold leaf electroscope.

One of the most sensitive forms, shown in Figure 335, is known as the gold leaf electroscope. It consists of a brass plate or knob, from which extends a brass rod having two gold or other metallic leaves attached at the lower end. The whole is supported by a glass jar for insulation and the protection of the leaves from air currents. When the plate receives a charge by contact with an electrified body, the whole metallic

part acquires the same kind of charge; hence the gold leaves, being electrified similarly, repel each other and continue to diverge as long as this charge, positive or negative, remains undisturbed on the electroscope.

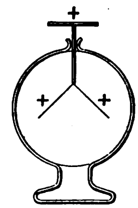


FIG. 336.—The electroscope is charged positively.

242. Induction. Charging by Induction. — Let us suppose that the electroscope has received a positive charge by contact with a glass rod, and the leaves are separated, as shown in Figure 336. If a negatively charged piece of vulcanite is now brought slowly toward the plate, the leaves will gradually fall toward each other until they show no charge. As we remove the vulcanite the leaves again diverge. Plainly, the charge was not removed from the electroscope, but it was only attracted away from the leaves by the negatively electrified vulcanite. If we next bring a positively charged glass rod toward the positively charged electroscope, the leaves will diverge more than before, showing that a part of the positive charge which was in the top of the electroscope has been repelled to the leaves. The leaves again return to their original divergence when the glass rod is withdrawn, for the charge again becomes distributed over the whole electroscope.

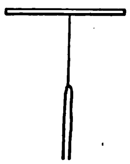


FIG. 337. — An uncharged electroscope without the jar.

Let us next suppose that the electroscope is without a charge (Fig. 337). As the charged glass rod is brought toward the top, the leaves diverge (Fig. 338), but if it is taken away again, the leaves collapse. When the glass rod is near, the leaves are charged with positive and the top plate with negative electrification. If instead of the glass rod the electrified vulcanite is now similarly used, the positive electrification is attracted to the top and the negative electrification is repelled to the leaves

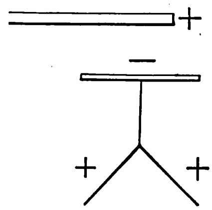


FIG. 338.—The action of a positively charged body upon the electroscope.

(Fig. 339). Again, the withdrawal of the electrified body leaves the electroscope uncharged. The action of either the electrified glass or of the electrified vulcanite on the unelectrified electroscope is called *induction*. In general, *when an electrified body is brought near to an unelectrified conductor, induction occurs*, in consequence of which the *near* part of this conductor acquires a charge *opposite* in kind to the inducing charge, and the *distant* part of the conductor acquires the *same kind* of charge as that on the inducing body.

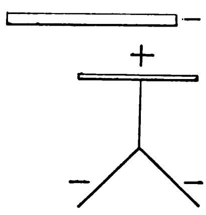


Fig. 339. — The action of a negatively charged body when near the electroscope.

In Figures 340 and 341 an original charge is supposed to be given to each insulated sphere and the induction takes place in each insulated cylinder, as indicated by the signs. If each of the cylinders is connected with the earth by a conducting body and then disconnected, upon removing the positively charged sphere its associated cylinder will have a negative charge, and when the negatively charged sphere is removed its associated cylinder will have a positive charge. This method of charging, in which the original charge is not conducted to the second body, is known as *charging by induction*. Since the inducing spheres have lost none of their charges, the process may be repeated indefinitely.

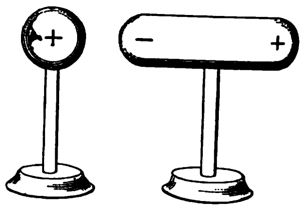


Fig. 340. — The induction produced by a positively charged body — the sphere.

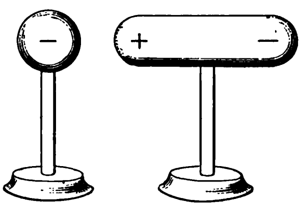


Fig. 341. — The inductive action of a negatively charged body.

243. Difference in Potential. — Let us suppose that we have two insulated brass spheres of the same size with equal charges, positive or negative

(Fig. 342). If we now connect the two spheres by a small wire held by a nonconducting silk thread, each will remain charged as before. Let us next give to one of the spheres a positive and to the other an equal negative charge, and again connect them with the wire (Fig. 343). This time both spheres are discharged. An energy change, commonly called *a flow of electricity*, has in this case taken place between the spheres through the connecting wire. Naturally it is common practice to say that the direction of the flow is from the body having the positive charge to that which has the negative charge.

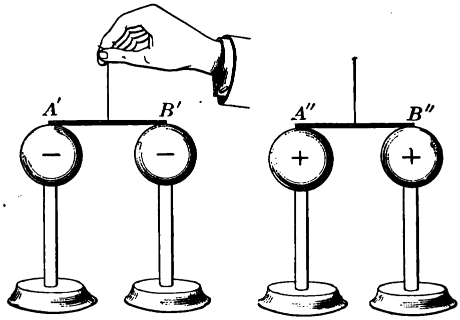


FIG. 342. — Showing the conditions under which no discharge takes place; no difference in potential.

From what has already been said in respect to the terms *positive* and *negative*, this so-called direction of the flow must be accepted, not as something that is actually known, but simply as a convenient and universally used method of stating that there is an energy transfer between the bodies. That difference between the electrical conditions of A''' and of B''', which produces the transfer of energy or the electric discharge from one to the other, is called *a difference in potential*, or simply *potential difference* (P. D.). A difference in potential is to be regarded as a condition essential to the flow of electricity through a conductor connecting the two bodies. If each of the two bodies A''' or B''' were separately connected to the earth by a wire or other

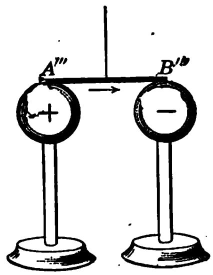


FIG. 343. — A discharge takes place. The sphere A''' is said to have a positive potential.

conductor, a flow would likewise occur in each case. Using the customary language, the direction of the flow would be from the positively charged body A''' to the earth, and from the earth to the negatively charged body B'''. Both bodies would then be discharged. Since, as has been stated, the reason for an electric discharge or flow is a difference in potential, we conclude that before the discharge there must have been a difference in potential between each of these bodies and the earth. Believing that the electrical condition of the earth is practically constant, we *select the earth as the standard and call its potential zero*, and then a positively electrified body is said to have a positive or higher potential and a negatively electrified body a negative or lower potential than that of the earth.

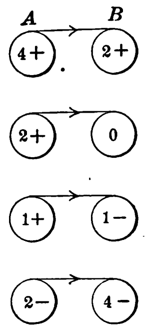


Fig. 344. — The direction of the discharge or flow is from the higher to the lower potential.

In order to have a difference in potential between two bodies, it is not necessary that one should be positively and the other negatively electrified, or that one should be charged and the other without charge. Both bodies may be charged positively or both negatively, and yet a difference in potential may exist between them. For example, let us suppose that A (Fig. 344), one of two equal spheres, has 4 positive units of charge and the other B has 2 positive units, there is the same difference of potential between them as though A had 2 positive units and B no charge at all, or A 1 positive unit and B 1 negative unit, or A 2 negative and B 4 negative units of charge. In all four cases there is the same difference in potential between the two bodies, and since B has the lower potential in every instance, the direction of the discharge is from A toward B in each case.

244. Illustrations of Potential Difference. — Potential bears a relation to electricity similar to that of temperature to heat or that of intensity of pressure to a fluid. Heat always flows,

by conduction, from places where there is a higher toward places where there is a lower temperature, but not always from bodies in which there is a greater to those in which there is a less quantity of heat. A very little heat gives some bodies a very high temperature. Similarly, electricity always flows by conduction from a body of higher potential to one of a lower potential, but not always from a body in which there is more to one in which there is less electricity. To bodies having a small *capacity* a small charge gives a high potential. The centigrade zero of temperature is the temperature of a common body, melting ice, taken as a starting point in reckoning temperature, and does not mean without heat. Further, when we say that the earth is at zero potential this must not be taken to mean that the earth has no electricity, but that the potential of the earth is taken as a starting point in reckoning potential. Let *A* and *B* (Figs. 345 and 346) represent two jars connected by a tube which can be opened and closed at *C*. Whether the fluid will move from *A* to *B* or the reverse, when *C* is opened, depends upon the relative intensity of pressure, and not upon the quantity of fluid in each. This is true whether the fluid is water (Fig. 345) or air (Fig. 346). Fluids move through a conducting pipe from the points of higher toward the points of lower pressure. Similarly, electricity flows through, a conducting body from points of higher to points of lower electrical pressure or potential. If we were to pump air into each of two flasks, of different size but with the same strength of walls, until they burst, the small one

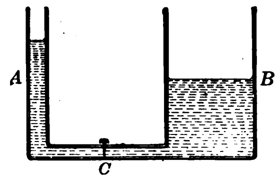


FIG. 345.—Water flows through the tube *C* in the direction of the greater intensity of pressure without reference to the quantity of water.

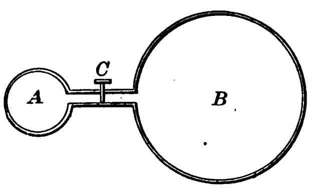


FIG. 346. — When *C* is open the air flows from the vessel in which the pressure is greatest.

would burst with less air but the same intensity of pressure. This illustrates how a very small electric charge may in some cases produce high enough potential to cause a discharge or a breaking through of the surrounding air or other material when even a larger charge is readily retained on another body.

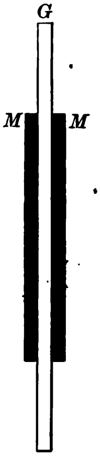


FIG. 347.—The condenser. The conductors MM are separated from each other by the glass G.

245. **The Condenser.** — A conductor charged to a high potential, even when insulated, is liable to lose its charge. If a second conductor is placed near the first, induction takes place between the two, through the nonconducting air, and the potential of the first conductor is thus lowered without decreasing its charge. In other words, the capacity of each conductor has been increased. The charge on each conductor may then be increased with less danger of escaping. This arrangement, which consists of two conductors and a nonconductor, or *dielectric* between them, is called *a condenser*. It may consist of two metal plates (M) with a considerably larger glass plate (G) between them (Fig. 347), or of a glass jar coated with tin foil within and without, excepting near the top (Fig. 348). The latter form of condenser is called the Leyden jar. For convenience in charging and discharging, the top of the jar is closed by a dry wooden block through which passes a brass rod having a knob at the top and a piece of chain attached, extending to the tin foil at the bottom of the jar. The Leyden jar, or other forms of condensers, may be charged by electrifying, either positively or negatively, one of the conductors, while the other is connected with the

FIG. 348.— Leyden jar.

earth, or one conductor may be electrified negatively, and the other positively. We may think of each of these charges as attracting and holding the other, hence they may be increased until their attraction becomes so strong that they break through the dielectric, — the air or glass. Ordinarily the Leyden jar is discharged by connecting the two coatings of the jar with a conductor.

246. **The Oscillatory Nature of the Discharge.** — One of the most interesting features of the condenser is the character of its discharge. If one end of the discharging conductor is placed against the outside coating and the other end brought toward the inner knob, the discharge takes place before the knob is quite touched. As a result, instead of having a transfer of energy sufficient to neutralize or to bring both sides to the zero potential, there is an excess of flow, so that the side which was at first negative becomes positive, and the other side becomes negative. This is quickly followed by another over-discharge, in the opposite direction and this by another, etc., each growing weaker until finally the jar is completely discharged, all taking place in a very small fraction of a second. This oscillatory discharge gives rise to waves in the surrounding ether which are of much greater wave length than those of light and are known as electric or Hertzian waves. They are used in the commercial process known as "wireless telegraphy" (sec. 300).

247. **Electrical Machines.** — The early electrical machines consisted of glass cylinders or plates mounted on axles so that they could be electrified by their rubbing against some material as they rotated. Much better machines are now constructed, which depend upon the process of induction for their electrification. In the best of these the details of construction are numerous and the explanation is complicated. Apart from the entertaining experiments which can be performed by them, these machines have little value for any but the advanced

student or the specialist. For a description of these machines the student may consult the larger treatises on electricity.

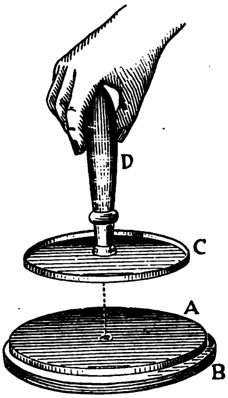


FIG. 349. — Electrophorus.

248. The Electrophorus. — The main principle involved in all the induction machines is readily exhibited by a very simple device called the *electrophorus* (Fig. 349). A shallow metal dish is filled with a cake of sealing wax A. This can be electrified negatively by rubbing it with fur or flannel. A metal disk *C*, somewhat smaller than the cake of sealing wax, is attached to a glass handle *D*, and brought near the electrified sealing wax (Fig. 350). The negatively charged sealing wax acts inductively upon the metal disk, thus electrifying the lower side positively and the upper side negatively. If the disk is withdrawn, it is found to be unelectrified. But if the disk, when in the position shown in the figure, is connected to the earth for an instant by touching it with the finger, or other conductor, the upper surface will then discharge and only the positive charge remain. If now the disk is removed from the sealing wax by its insulating handle, it will have a positive charge. Instead of holding the disk with a visible air space between it and the sealing wax the two may be placed in contact and used with the same result as described. A layer of air remains between the disk and the wax everywhere excepting at the few points of contact.

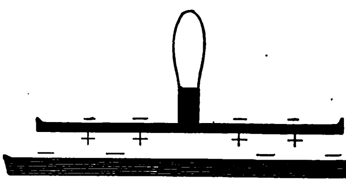


FIG. 350. — Showing the inductive action of the negative charge, on the sealing wax, upon the metal disk.

249. The Electric Spark. — The fact that an electric discharge through the air between two conductors is commonly

accompanied by a production of light and sound is the source of a common misunderstanding as to the nature of electrical energy. Electricity cannot be seen or heard. The visible spark is only so much light produced by a transformation of a part of the electric energy into light. In a similar manner another portion of the electric energy is converted into sound energy. The light and sound which we perceive are not the electric energy, but they represent that portion of it which the poorly conducting air or other substance converts into these other well-known forms of energy. A good conducting material like a thick copper wire generally transmits the electric energy without producing light or sound.

250. **Lightning.** — In some manner not thoroughly understood electrification is produced in the atmosphere. Accompanying the rapid condensation of vapor and the growth of tiny raindrops into larger ones, there is a rapid change in the potential at certain places in the clouds. Following this may come a discharge from cloud to cloud or from a cloud to the earth, forming sparks with an accompanying sound similar to that which is noticed in experiments, but with a greatly increased intensity. The high humidity and consequent rapid condensation which is possible for a given amount of cooling in summer, make the occurrence of thunder storms more frequent at that season.

Questions and Problems

1. What is the standard method of producing positive electrification? May positive electrification be produced in any other way? Why is it called positive?

2. Is attraction or repulsion the more reliable indication of the kind of electrification? Why?

3. Explain why a metal ball suspended by a silk thread between two bodies, one of which is charged positively and the other negatively, flies back and forth between the two bodies.

4. Why can you not electrify a metal rod when you hold it in the bare hand? Suggest some way of holding or supporting it so that it may be electrified in the usual way.

5. State the important differences between electrification and magnetism.

6. If a gold leaf electroscope is charged negatively and a glass rod which has been rubbed with silk is moved toward the top of the electroscope, what will be the effect on the leaves?

7. If a piece of electrified sulphur is brought near a negatively charged electroscope and the leaves diverge further, is the electrification of the sulphur positive or negative?

8. If a charged Leyden jar is standing on a plate of glass and the knob is touched with the finger, only a slight discharge occurs. If the outside of the jar is touched, another slight discharge occurs. If the sides are thus touched alternately, a succession of small discharges takes place until the jar is finally discharged. Explain.

XVI. CURRENT ELECTRICITY

Sources of Electric Currents

251. What is an Electric Current? — Attention has already been called to the fact that when a copper wire is used to connect two conductors one of which is positively and the other negatively electrified, a transfer of energy called an electric discharge takes place through this connecting wire. In the early years of its history, when electricity was called a fluid, the process of transfer believed to be taking place in the connecting wire was naturally called a current. Though our ideas of the nature of electricity have undergone many changes, we still retain the term *electric current* to express the transfer of energy which seems to take place through a conductor when it is connecting two other conductors at different potentials. By this we do not mean to claim that it is known that this energy flow is within the wire rather than in the space around it, but we simply assert that the flow is directed by the wire.

Sources of Currents. — The current between two oppositely charged bodies will last for such a small fraction of a second as to be of no practical value, unless we can find some way to recharge the bodies continuously; that is, we must secure a method of restoring the difference in potential between them as rapidly as the conductor is neutralizing it. A continual charging of the bodies requires the doing of work; that is, it requires that energy of some kind must be continuously converted into electrical energy. There are two kinds of energy which are most generally used for this purpose. They are (1) *chemical energy*, which furnishes the current in the various

forms of the *voltaic cell* or galvanic battery, and (2) *mechanical energy*, which is the source of the current in the various forms of the *dynamo*.

252. **The Voltaic Cell; Simple Form.** — A glass jar containing dilute sulphuric acid (1 part acid with 10 to 20 of water) and two metallic plates, one of copper, the other of zinc, constitutes a simple form of voltaic cell or battery (Fig. 351). It can be shown, with sufficiently delicate apparatus, that the copper in this cell has a positive charge or + potential and the zinc a negative charge or — potential. If these metals, when not touching each other, are connected, outside the cell, by a conducting substance, as a copper wire, a *transfer of energy* takes place which is identical with that which we have already called an *electric current.* The end of the copper plate projecting above the liquid is called the *positive pole or electrode* and the corresponding end of the zinc is known as the *negative pole or electrode.* When the outside conductor is not connected to the poles, the *potential difference* (P.D.) between the copper and the zinc, that is, the cause of the current, is called the *electromotive force* of the cell, commonly written E.M.F.

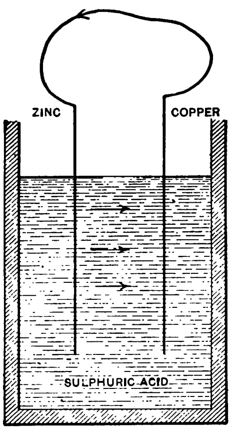


FIG. 351. — Voltaic cell.

How the Current Originates. — The energy required to maintain the difference in potential (E.M.F.) between the plates is furnished by the dissolving of the zinc in the acid, a chemical process much like the burning of fuel in air. The difference in potential may be considered as originating at the surface of the zinc where the chemical action occurs. At this point the zinc has the lowest and the liquid in contact with it the highest potential. The acid is separated or broken up into two parts

called *ions*, one (SO_4) combining with the zinc, and the other, hydrogen (H_2), passing over to the copper plate. The negative ion, SO_4, carries a negative charge to the zinc, and the positive ion, hydrogen, a positive charge to the copper. (This part of the action in a cell cannot be appreciated thoroughly until the student has had a course in chemistry.)

The So-called Direction of the Current; The Electric Circuit. — Beginning at the surface of the zinc, the course of the current or the direction of transfer of the positive electrification may be traced through the liquid to the copper plate, to the wire, to the zinc plate, to the starting point, thus making a complete *electric circuit.* This does not mean, however, that the current begins at this particular point in the circuit earlier than at other points. We believe that when the circuit is closed, that is, when the two poles are connected by a conductor, there is an equal current at all points along the circuit both within and without the jar at practically the same time. The disconnecting of the conducting material of an electric circuit, at any point either within or without the cell, called *breaking the circuit,* stops the current at once throughout the entire circuit.

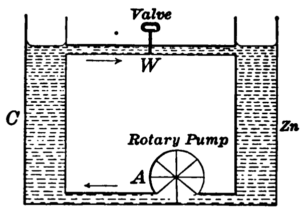


FIG. 352. — An illustration in which the production of an electric current is compared to the production of a current of water.

An Illustration showing how the Current is Produced. — The manner of production of an electric current may be better understood by making a comparison with a mechanism which might be used for the production of a continuous circulation of water. Let C (Fig. 352) and Zn represent two jars connected by two tubes, one (A) having a rotary pump, the other (W) having a stopcock or other method of stopping the flow. Let us suppose that the jars are filled with water to the level of W and the pump is started. On account of the action of the pump water will flow from Zn to C through the lower pipe, the level

of the water rising in C and falling correspondingly in Zn. If the connecting tube W is open, in its effort to neutralize the difference in level, water will flow from C to Zn and we have a continuous circulation as long as the pump is working. If we close W, the level in C will rise as much higher than that in Zn as the driving force at the pump is capable of sending it, or until the back pressure in C stops the pump. If the pipe W is now opened, the flow of the water out of vessel C decreases the pressure there and the pump will start. If for any reason the pump fails to work, of course the current of water ceases, even when W is open. Vessel Zn is similar to the zinc plate in the cell, and the power driving the pump resembles the chemical action. The vessel C is like the copper plate, and the tube W when open is like the connecting wire. The greatest pressure intensity which the pump is capable of producing when the tube W is closed is similar to the difference in potential or electromotive force of the cell when the wire is disconnected — the circuit open. The tube A is like the acidified liquid in which the chemical action occurs and which transmits the current from the zinc to the copper. Note that when a pipe transmits a current of water we say it is open, but when a circuit transmits an electric current we say it is *closed.*

253. **Local Action; Amalgamation.** — A piece of *pure zinc* will not dissolve in the dilute sulphuric acid of the cell unless the copper plate also is in the acid and connected to the zinc by a wire; that is, the electric circuit must be complete or closed. But zinc, of the quality which is ordinarily used for cells, will readily dissolve when the circuit is open or even when it is in the acid alone. This is due to the fact that common zinc is very impure. These impurities act in relation to the zinc like small copper plates, hence small currents are formed from these particles to the zinc they touch. The production of currents in this way is known as *local action.* It not only results in a waste of the zinc when the circuit is open, but

diminishes the main current when the circuit is closed. Coating the zinc with a thin layer of mercury, a liquid which dissolves and brings to the surface of the plate a solution of the zinc, greatly diminishes the local action. The process of coating the zinc with mercury is commonly known as the *amalgamation* of the zinc.

254. **Polarization.** — In the simple voltaic cell, shortly after the circuit is closed, a layer of hydrogen forms on the copper plate, and the current rapidly decreases in strength or even practically ceases (Fig. 353). This accumulation of the hydrogen on the copper is technically known as the *polarization of the cell.* Because hydrogen is a poor conductor and also because it diminishes the electromotive force of the cell, polarization constitutes a most serious defect in many kinds of voltaic cells. In general, polarization may be prevented either by using some plan of removing the hydrogen, as fast as it is produced, or by using such materials in the construction of the cell that no hydrogen can be liberated.

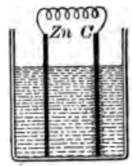


FIG. 353. — Polarization. The hydrogen bubbles are accumulating on the carbon plate.

255. **Conductance of the Cell; Resistance.** — The liquid between the plates of a cell is a necessary part of the conducting material in the circuit. If this liquid is a poor conductor, the current will on that account be lessened. For a given liquid the conductance of the cell is increased (1) when the plates are brought nearer together, (2) when the plates are increased in area of surface presented to the liquid. Using the term resistance as the reciprocal of conductance, we may express the same ideas thus: The current will increase when the resistance of the cell decreases. The resistance of a given kind of cell can be decreased (1) by bringing the plates nearer, and (2) by making the parts of the plates within the liquid larger. Conductance and resistance are more fully discussed in section 275, page 361.

256. Varieties of Cells. — The best practical cell would be that which combined in itself the following points:

(1) The highest E. M. F.

(2) No polarization.

(3) The greatest conductance (least resistance).

(4) The greatest economy.

No one cell stands first in all these respects. Many forms of cells have been invented, of which we shall describe only a few; for the dynamo, as a source of currents, has quite generally displaced the voltaic cell except for minor uses.

The Daniell Cell. — This form of voltaic cell (Fig. 354) consists of a glass jar containing a large copper plate immersed in a solution of copper sulphate (blue vitriol). Within the jar is a small porous or unglazed earthen jar containing the zinc plate surrounded by dilute sulphuric acid or a zinc sulphate solution. The E. M. F. of a Daniell cell is not very high.

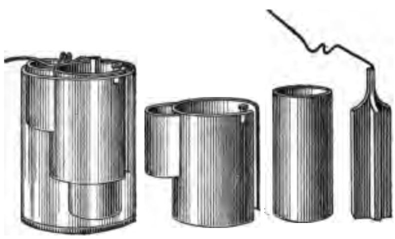


FIG. 354. — A Daniell cell.

Since the current can pass through the liquid in the pores of the jar only, the conductance of this cell is small (resistance large) unless the plates are very large. In the working of this cell the copper contained in the copper sulphate solution is deposited upon the copper plate where the hydrogen was deposited in the simple cell previously described, hence there is no polarization and the E. M. F. is quite constant. If the circuit is left open too long, the fluids mix through the porous jar and the working of the cell is interfered with. On account of the steady current which it may furnish, the Daniell cell is well suited for laboratory experiments.

The Gravity Cell. — This cell (Fig. 355) differs from the Daniell only in minor points. The copper plate, surrounded

with the copper sulphate solution and crystals, is placed at the bottom of the jar. The zinc plate is suspended in the dilute acid or zinc sulphate solution, near the top. The difference between the densities of the two liquids prevents rapid mixing, hence the porous partition of the Daniell cell may be omitted. Its action is identical with that of the Daniell, but it requires some time after being set up to get into a good working condition. Since shaking would mix the liquids, the gravity cell cannot be readily moved. On account of its steady current, its simplicity and economy, this cell is well suited for operating telegraph instruments and for other closed circuit work.

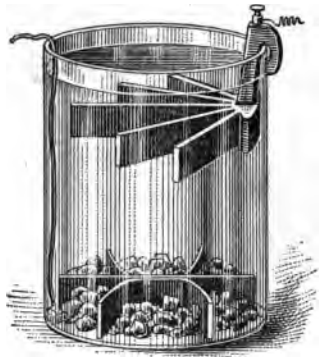


FIG. 355. — The gravity cell.

The Bichromate Cell. — If potassium bichromate or chromic acid is added to dilute sulphuric acid, and carbon is used for the positive plate with zinc as the negative, we get a form known as the bichromate (Grenet) cell (Fig. 356). Its electromotive force is high, and since the plates may be placed near each other the conductance is high (resistance small). It polarizes when used for a considerable time, and the zinc wastes when the circuit is open, hence the zinc should be removed from the liquid when the cell is not in use. This cell is well suited for class experimenting, where a strong current is desired for a short time.

FIG. 356. — A bichromate cell.

The Leclanché Cell. — In the original form of these cells the manufacturer places the carbon or positive plate in a porous jar and packs around it a mixture of powdered carbon and manganese dioxide ($Mn\ O_2$) to act as a depolarizer. This porous jar is then sealed and placed in a glass jar containing a solution of sal-ammoniac or ammonium chloride (NH_4Cl) into which is placed a rod of zinc. In a more recent form of this cell the manganese dioxide is combined with the carbon in one solid plate which is placed with the zinc directly in the ammonium chloride solution (Fig. 357). This cell has a fairly high E. M. F. It polarizes quickly, but recovers completely when the circuit is open. Its conductance is low (resistance high). It is well suited for ringing bells, operating telephone transmitters, and other light work where the circuits are generally open.

FIG. 357. — A Leclanché cell.

Dry Cells. — There are many modifications of the Leclanché cell sold under various names. In one form the zinc plate serves as the jar, and a mixture of the ammonium chloride and other materials in the form of a paste are put into the zinc jar along with the carbon plate, which latter is then surrounded with the manganese dioxide in much the same way as in the Leclanché cell. The top of the jar is sealed to prevent the paste from drying and the cell is then called a dry cell.

QUESTIONS AND PROBLEMS

1. What are the essential parts of a voltaic cell? Which element usually has the negative charge?
2. What is the meaning of the term *pole* or *electrode* in connection with a cell? Compare with the meaning of the term pole as used in connection with magnets.
3. In a voltaic cell with carbon and zinc as the two elements, state the so-called direction of the current (*a*) within the cell, (*b*) in the out-

side connecting conductor. Is this the direction of the positive or of the negative discharge?

4. Applying the term *potential* to the plates of a cell, state where the potential is said to be highest. Where the lowest.

5. What is the meaning of the term *electromotive force of a cell?* Give an equivalent term.

6. What is polarization? Why is it spoken of as a defect of a cell? How may it be prevented?

7. What is meant by the term *local action?* How may it be decreased?

8. What is the meaning of the term *battery circuit?* When is a circuit said to be open? When closed? What is then the meaning of the expression an "open circuit" system? A "closed circuit" system?

9. What is meant by the conductance or resistance of a cell?

10. State the conditions which would give a steady current. A strong current.

Effects of Electric Currents

257. The Action of a Current upon a Magnet. — A copper wire, whether insulated or not, has, ordinarily, no effect upon a magnetic needle. If, however, the wire is placed parallel to and near a pivoted magnetic needle or a compass, and if the two ends of the wire are connected to a voltaic cell, the needle will be rotated more or less from its original position, as shown in Figure 358.

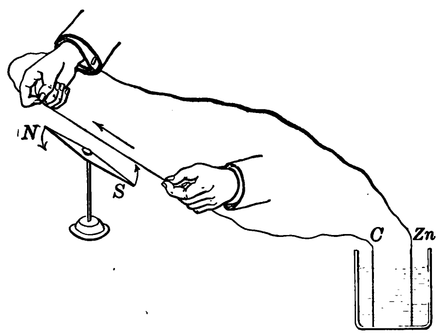


Fig. 358. — A current flowing northward above a magnetic needle turns the north pole toward the west.

The demonstration of the action of a current upon a magnet is frequently referred to as "Oersted's experiment." In the case shown in Figure 358, the wire being above the needle and the current direction northward, the north end of the needle is rotated westward and the south end eastward. Changing the

position of the wire, with reference to the magnet, changes the direction of the motion of the poles. Thus when the wire is placed beneath the needle, the north pole is rotated eastward instead of westward provided the current continues to flow toward the north (Fig. 359). If we hold the current-bearing wire in such a way that the current flows southward near the needle, each pole moves in a direction opposite to that given for each of the two positions shown in Figures 358 and 359. If the current-bearing wire is held at the side of the needle, one of the poles will be tilted upward and the other downward, provided they are free to move in those directions. We see, then, that a current flowing parallel to the length of a bar magnet, in either direction or in any position relative to the magnet, always acts upon it in such a way as to rotate the magnet *toward* a position in which the length of the magnet will be at right angles to the current. The amount of this change in direction of a needle, in any case, depends upon the magnetic strength of the needle, the distance of the wire from its poles, and the strength of the current in the wire. The final direction of the needle cannot differ from the current direction more than 90°, though it may be anything less.

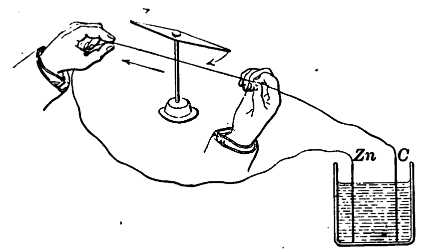


FIG. 359. — When the current is below the needle and flowing northward, the north pole is turned toward the east.

Ampere's Rule. — Since the effect of the current upon the needle is rotational, the one pole always moving toward the east when the other goes toward the west, we may always state the direction by giving attention to the north pole alone. The following, a modification of Ampere's rule, is a convenient rule for relating the direction of the rotation of the needle to the direction of the current: *Place your right hand against the wire,*

palm toward the needle with the fingers pointing in the direction of the current; the extended thumb will always point in the direction toward which the north end of the needle is deflected. Test this rule for all positions of the wire and all directions of the current. If the straight lines in Figure 360 represent the direction of the current, the circles with their arrow heads will represent the directions of the motion of the north pole when a magnet is placed in any of the different positions around the current.

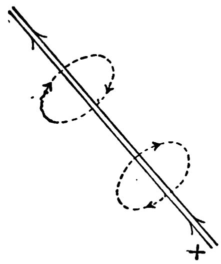


FIG. 360.— Showing the direction of the lines of force around a conductor in which there is a current.

258. Magnetic Field around a Conductor having a Current. — The action of a current upon a magnet shows that around a conductor there is a magnetic field which appears and disappears with the starting and stopping of the current. The presence and direction of the lines of force in this magnetic field can be readily shown by passing a wire vertically through a hole in a piece of cardboard and sending a strong current through the wire. If iron filings are now scattered over the level board, they will arrange themselves in concentric circles around the wire (Fig. 361). A small compass placed on the cardboard shows that the direction of the lines of force or magnetic flux around the conductor sustains the same relation to the direction of the current as that already indicated in the preceding section and marked in Figure 360. The magnetic intensity at any point of the field around a straight wire increases with the strength of the current and decreases as the square

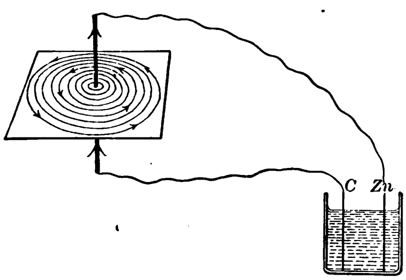


FIG. 361.—To a person looking along a conductor in the direction of the current, the lines of force have a clockwise direction.

of the distance of the point from the wire increases. If the wire is bent into the form of a circle, the lines of force around the different parts of the conductor will all have the same general direction within the circle (Fig. 362). The intensity of the field can be increased by sending the current a greater number of times around the circle.

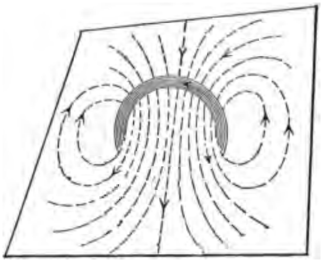


FIG. 362. — Showing the lines of force within and around a coil which is carrying a current in the anticlockwise direction or in the direction of the arrow.

259. The Galvanoscope and Galvanometer. — The action of the current upon a magnetic needle furnishes a simple method of *detecting a current* and *determining its so-called direction.* Any instrument used for these purposes is called a *galvanoscope.* If the conductor is so arranged that the current, instead of passing parallel to the needle once only, is carried entirely around it (Fig. 363), the effect of the lower current upon the needle will be in the same direction, hence added to that of the upper current; for the lower current is opposite to the upper, in respect to both direction and position, hence as shown by the right-hand rule the direction of the rotation it produces will be the same as that of the current located above. A second turn of the wire will produce an effect in the same direction, hence it adds to the first. By passing the wire around the needle many times and thus multiplying the effect, the galvanoscope can be made very sensitive. In order to compare the strength of the currents which may be sent through such an instrument, it becomes necessary to measure the amount of the deflection of the needle in each case. This

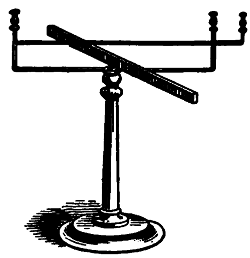


FIG. 363. — Apparatus of Oersted for studying the action of an electric current upon a magnet. A galvanoscope.

may be done by placing underneath the magnet a circle, graduated in degrees. Because the instrument is now capable of being used to measure relative strengths of currents, it is called a *galvanometer*.

260. The Tangent Galvanometer. — One of the simplest forms of galvanometer is shown in Figure 364. It consists of a ring of wood or other nonmagnetic substance on which is wound a number of turns of insulated wire. At the center of the ring is suspended or pivoted a small magnet to which is frequently attached a much longer pointer. A current flowing around the circle deflects the needle, the angle of the deflection being read by means of the needle itself or by the pointer. The angle of deflection of the needle does not increase at the same rate that the strength of current increases. This is because the restoring action of the earth upon the poles of the needle becomes greater when the angle between the needle and the magnetic meridian becomes greater. For this reason a deflection of 20°, for example, indicates more than twice the current shown by a deflection of 10°. Because it can be shown that the current strength varies as a certain value known as the tangent of the angle of deflection, this particular instrument is known as the tangent galvanometer.

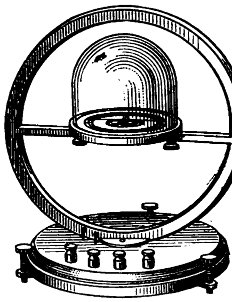


FIG. 364. — A tangent galvanometer.

261. The d'Arsonval Galvanometer. — Another form of galvanometer in common use is shown in Figures 365 and 366. In this instrument the coil C, consisting of a large number of turns of very fine insulated wire, is suspended by a fine wire between the poles of a strong horseshoe magnet. When a current goes through the coil, the action between its magnetic field and the field of the fixed magnet NS rotates the suspended coil instead of the magnet as it does in the tangent galvanom-

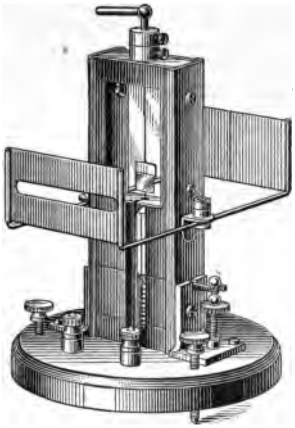


FIG. 365. — A d'Arsonval galvanometer.

eter. When the coil comes to rest, the lines of force through the coil have, in general, the same direction as the magnetic lines of the magnet, hence reversing the current in the coil reverses the direction of rotation. Because the permanent magnet does not move, it may be made very large, thus providing a strong magnetic field. This, combined with the large number of turns and consequently strong field of the light coil of wire, makes a very sensitive instrument, suitable for detecting and measuring very small currents only. An instrument of this type is usually called a d'Arsonval galvanometer.

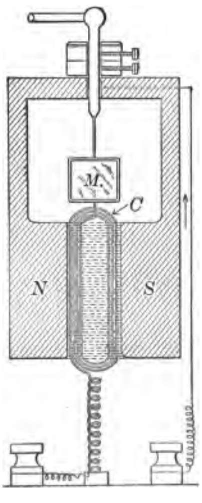


FIG. 366. — A d'Arsonval, showing the magnet, the coil C, and the mirror M, by which the deflection may be indicated.

262. How Electric Currents produce Magnets. — It has been found in the study of magnetism that a piece of soft iron is always practically free from magnetism unless it is near a permanent magnet; that is, unless it is placed in a comparatively strong magnetic field. If an insulated wire is wound a number of times around a piece of soft iron and a current is sent through this wire, the iron immediately becomes a magnet (Fig. 367). As soon as the circuit is broken the soft iron loses

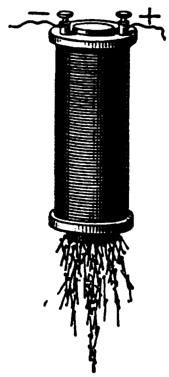
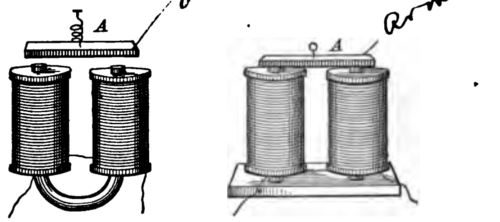


FIG. 367. — An electromagnet. Straight form with soft iron core.

its magnetism, just as it does when removed from the field of a permanent magnet. This again shows that a current of electricity flowing around a coil of wire produces a magnetic field similar to that produced by a permanent magnet. A coil of wire used for this purpose is frequently called a *helix* or *solenoid*. The iron within the coil is called the *core*. The ~~coil~~ armature of wire, together with its core, constitute the *electromagnet*, one of the most important instruments in the application of electricity. Electromagnets may be of any desired size or shape. Their magnetic strength depends upon the size and permeability of the core, the number of turns of wire in the coil, and the strength of the current in it. When the core of the electromagnet is made of soft or highly *permeable* iron, the magnetism comes and goes with the starting and stopping of the current, but when the hardest or most *retentive* steel is used as the core, a large part of the magnetism remains after the current ceases. Placing a steel bar within a helix which is bearing a current is the best method of making a strong permanent magnet.



I II

FIG. 368. — Electromagnets of the horseshoe form with armatures *AA*.

To find the North Pole of an Electromagnet. — The poles of an electromagnet can be determined by means of a compass, or when the current direction is known by using the following rule. *Grasp the coil with the right hand so that the fingers point around the coil in the direction of the current and the extended thumb will point toward the north pole of the core and also show the direction of the magnetic lines of force within the coil* (Fig. 369).

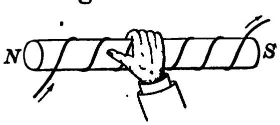


FIG. 369. — Showing how the north pole of an electromagnet can be related to the direction of the current.

The application of this rule shows that when looking toward a north pole of a coil or solenoid, the current traverses the coil counter clockwise (Fig. 370). On the other hand, when looking toward the south pole, the current direction is clockwise (Fig. 371).

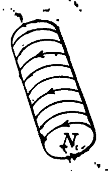


FIG. 370. — The direction of the current to a person looking toward a north pole.

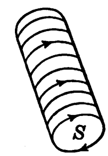


FIG. 371. — The direction of the current as it seems to a person looking toward a south pole.

The electromagnet is used in the electric bell, in the telegraph, the telephone, the dynamo, the motor, and indeed in connection with nearly all electrical appliances.

263. A Connection between an Electric Discharge and an Electric Current. — If a heavily insulated wire is wound loosely around a large steel needle and a Leyden jar is discharged through the coil, it will generally be found that the needle is magnetized, though often feebly so (Fig. 372). It will also be found, even when great pains are taken to connect the positive side of the jar to the same end of the coil, that different ends of the needle become the north pole in different trials. This is due to the oscillatory character of the discharge from the jar as already mentioned and as will be further referred to under the topic Wireless Telegraphy. We are justified in concluding that in every case of electric discharge, whether brief as is that of a highly charged jar or continuous as in the case of a battery, a magnetic field is produced by the motion of the charge.

FIG. 372. — The discharge of the jar magnetizes the iron in the coil.

QUESTIONS AND PROBLEMS

1. State your understanding of the difference between an electric charge and a current.
2. How can a magnetic effect be produced from an electric charge?

3. What is the meaning of the term *magnetic field?* How could you prove that there is such a field surrounding a conductor which is carrying a current?

4. A wire is carrying a current toward the north. Supposing that you are looking along the wire in the direction the current is flowing, state the direction of the magnetic force or flux in the field (*a*) beneath the wire, (*b*) on the left side of the wire, (*c*) above the wire, (*d*) on the right side of the wire.

5. A current is flowing south in a wire below a magnetic needle. Describe the effect upon the needle.

6. The current in a north and south trolley wire turns the north end of a needle, held below it, toward the east. What is the direction of the current in the wire?

7. In what direction would a current have to flow around an iron trolley pole to make the end in the ground a south pole?

8. State the difference in the results secured by using steel instead of soft iron as the core in an electromagnet.

9. If you face the end of a coil of wire around which a current is flowing in the direction of the hands of a clock, are the lines of magnetic force within the coil directed toward or from you? Prove your answer by the right-hand rule.

10. Why do two turns in a galvanometer coil produce a greater deflection of a magnetic needle within the coil than one turn produces?

264. The Electric Telegraph. — The electric telegraph in its simplest form requires (1) a source of current, (2) a line wire, (3) a device for quickly closing and opening the line circuit, and (4) an instrument which, placed anywhere on the line, will give an indication, by sound or otherwise, of the closing and opening of the circuit.

Batteries are used as a source of current in small offices, but dynamos are more economical where large demands exist. For the sake of economy the line wire may be made of iron, and the earth is used as one half of the circuit, both ends of the line being "grounded."

The device for closing and opening the circuit, called a key, is shown in Figure 373. The break between *A* and *B* is closed by pressing on the knob *C* of the lever *AE*, thus permitting a current to flow through the line wire. When

C is released, a spring pulls *E* down and again breaks the circuit. When not sending signals, the break at the key is closed permanently by a switch lever not shown.

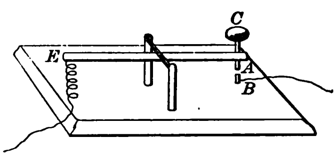


FIG. 373.—Showing the essential features of a telegraph key.

The current, which starts and stops upon the closing and opening of the circuit, operates an instrument on the line called the sounder. This receiving instrument consists of an electromagnet of the ⊔-form (*A*, Fig. 374) near which is placed a lever supported on an axis at *B* and having a bar of soft iron *C* directly above the electromagnet. When the current flows through the coils, the core becomes magnetized and attracts the soft iron bar of the lever, pulling it down, in spite of the spring, against the stop *D*, producing a sharp click. When the circuit is opened, the magnetism disappears from the electromagnet. The bar and lever being thus released, the spring is now able to pull the lever back against the set screw *E* with another but a different click. It is evident from this that the working of the key, with the accompanying starting and stopping of the current in the line wire, will be imitated by the motion and resulting clicks of the sounder lever. A number of sounding instruments can be simultaneously operated by the same battery and key, provided the line is a comparatively short one. On long lines the feeble current of the main circuit is not sent through the sounder, but through a similar instrument, the relay, which, though it works quietly, opens and

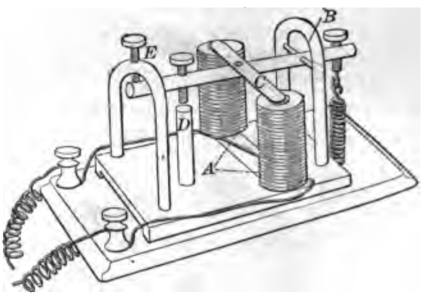


FIG. 374.—A telegraph sounder.

closes the circuit of a local battery connected with the sounder (Fig. 375).

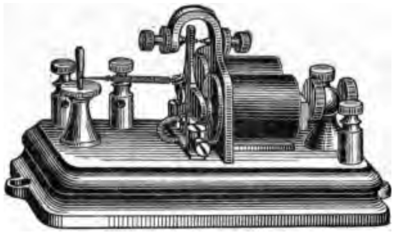


FIG. 375. — A relay.

265. The Relay. — The essential parts of a relay are shown in Figure 376. One end of the coil of the relay electromagnet *m* is connected to the line wire and the other end to the ground. A soft iron bar is attached to a lever *l*, which is held away from the magnet by a delicate spring *Sp*. At the top of the post *b* is an adjustable screw *n* so placed that it does not touch the bar when the spring holds the lever *l* away from the electromagnet. The post *b* is attached to one pole of

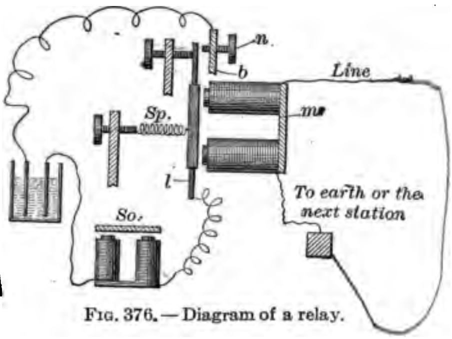


FIG. 376. — Diagram of a relay.

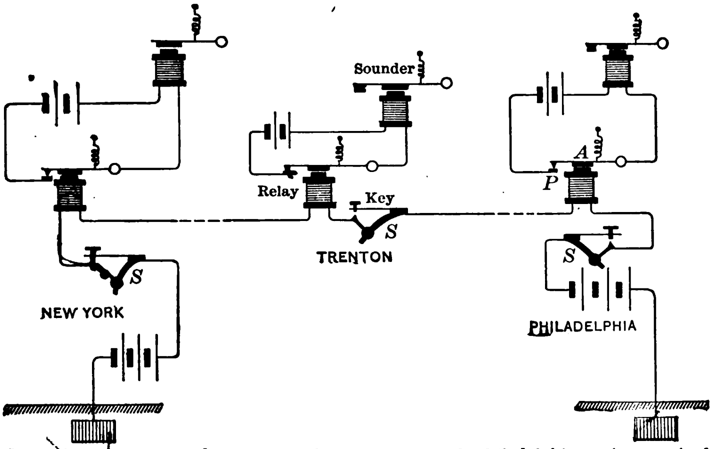


FIG. 377. — A telegraph system with New York and Philadelphia as its terminal and Trenton as an intermediate station

the local battery in the circuit of which is placed the sounder *So*, and the other pole is attached to the lower part of the lever *l*. When the key is closed at a sending office, the line current flows through the electromagnet of the relay. This is sufficiently magnetized to pull the light bar forward and bring the lever *l* gently against the screw *n*, thus closing the circuit of the local battery which produces a corresponding click in the sounder. When the line circuit is opened, the relay, by aid of the spring, opens the local circuit. A diagram of a working telegraph system is shown in Figure 377.

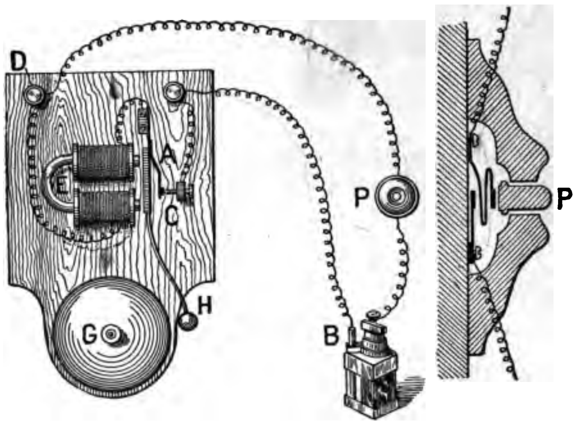


FIG. 378. — Electric bell and push button *P*.

266. The Electric Bell. — Another familiar and important application of the electric current for signaling purposes is known as the electric bell. The simplest form of the vibrating bell or common doorbell is shown in Figure 378. The post *C*, having an adjustable screw at the top, is insulated from the rest of the bell. When the bell is not working, a bar of soft iron ending in a clapper *H* is held against the screw *C* by a spring *A* at its upper end. One end of the wire of the electromagnet coil *E* is attached to the end of the soft iron bar and

the other leads to either pole of the battery B. The other pole of the battery is connected to the insulated post C. At any point in the circuit is inserted a push button P which closes the circuit at that point as long as the button is pushed upon, but opens it when the button is released. When the circuit is closed, the current flows around the electromagnet, which becoming magnetized attracts the iron bar, jerking the clapper against the bell G, at the same time breaking the circuit at the end of the set screw C. This break stops the current, and, the electromagnet having lost its magnetism, the spring pulls the clapper back to its former position against the screw C, thus restoring the current. Again the magnetism is produced, and the action described is repeated indefinitely as long as the circuit is closed at the push button, each make and break of the circuit producing a vibration of the clapper.

267. **The Heating Effects of Currents.** — A perfect conductor, if such existed, would transmit all the electrical energy given to it. Every conductor, on account of its resistance, transforms a part of the energy of the electric current into other forms of energy, heat being the form most readily produced. If we take a thin platinum wire and send through it a current of considerable strength, a large part of the energy will be converted into heat, the wire rising in temperature, even becoming red-hot or white-hot when the current is sufficiently strong. Other conductors besides platinum may be thus used for producing heat, but many substances will melt or burn before they become red-hot. This heating effect of the current explains how certain metals or alloys called *fuses* are used in electric circuits. On account of its low melting point, the fuse melts and breaks the circuit when a current too strong for the safety of a motor or other apparatus is being sent through it. Coils of wire of proper size and material are frequently used as *heaters* in trolley cars, electric irons, electric ovens, and for heating purposes generally. At Niagara Falls and elsewhere, the intense heat from powerful

electric currents is used in the manufacturing of carborundum, calcium carbide, and other useful materials.

268. Production of Light from the Electric Current. — A current in a conductor always produces some heat, but it is only when the resistance of the conductor is quite large or the current very strong that the temperature becomes high enough to produce light. To be suitable for the production of light, the conducting substance must have a very high melting point and must not burn. To this end a charcoal or carbon wire or filament is well suited as regards melting point, but because it burns rapidly when in air, it must be inclosed in an air-tight globe from which the air is removed as completely as possible. This gives us the familiar *incandescent* or *glow* lamp (Fig. 379). The outer brass ring, with the screw, is attached to one end of the carbon filament by a platinum wire running through the wall of the glass bulb, and the small brass disk at the end of the lamp is attached to the other end of the carbon filament in a similar way.

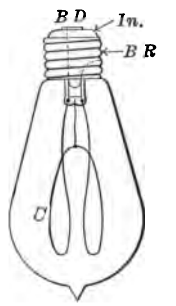


FIG. 379. — The brass ring *BR* is insulated from the brass disk *BD*.

In the *arc light* two rods of carbon are placed end to end in contact with each other. A strong current is sent across the junction and the rods are then automatically pulled slightly apart by a rather complicated regulator at the top of the lamp (Fig. 380). If the distance between the carbons is not too great, the current continues across the intervening high resistance gap and an intensely high temperature with a brilliant light is the result. When a direct current is used, the end of the positive carbon wastes faster and gives out more light than that of the negative. The regulating mechanism keeps the carbons at the proper distance. Placing the ends of the carbons within a practically air-tight globe and thus

shutting out the oxygen of the air greatly diminishes the waste of the carbon. This is the common practice in recent forms of arc lights.

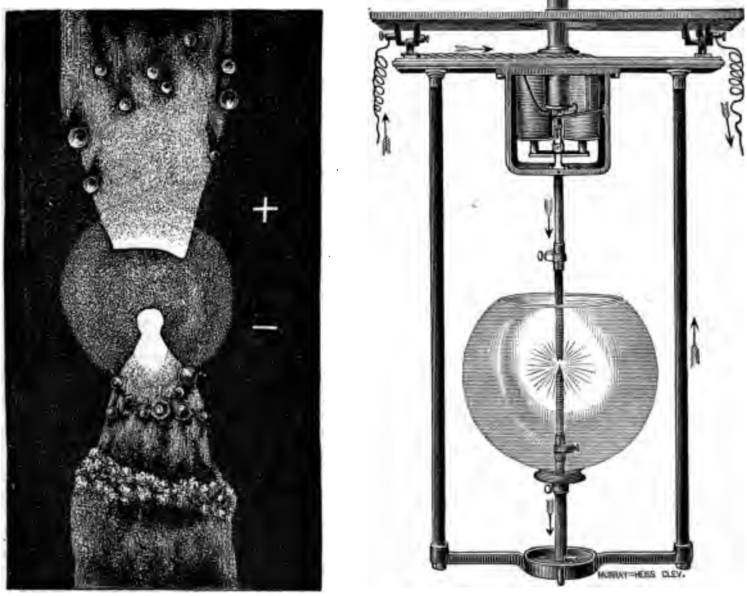


FIG. 380. — The electric arc between two carbon poles.

269. The Chemical Action of the Current. — Water is composed of two substances or elements, known as oxygen and hydrogen. When a current is being transmitted by water which contains some acid, the water is gradually separated into these two elements. The oxygen appears, as a gas, at the place where the current enters the liquid; and the hydrogen appears, as an entirely different gas, at the place where the current leaves the liquid. If we use a suitable tube to hold the water we may collect these gases separately (Fig. 381). Since such processes as the forming of compounds from elements and the breaking up of compounds into elements are called chemical

processes, this action of the current upon the water as just described is known as a *chemical action* of a current. Because it consists in a separation or analysis by electrical means, the process is called *electrolysis* (electro-analysis). Any compound which undergoes this chemical action of the current or electrolysis is called an *electrolyte*. The conductor by means of which the current enters the liquid is called the *anode* and that conductor through which it leaves the liquid is called the *cathode*. When water undergoes electrolysis, the oxygen appears at the anode and the hydrogen at the cathode. The two parts into which a compound molecule is separated by electrolysis are called *ions*. One of these ions always has a positive charge and the other an equal negative charge. Figure 382 represents a jar containing a solution of copper sulphate, into which are placed two platinum plates attached to a battery. The plate attached to the positive pole of the battery is the anode, that attached to the negative pole is the cathode. After the current has been flowing for a short time a deposit of copper is found on the cathode. All other metals, when set free from their compounds by electrolysis, appear, like the copper, on the cathode.

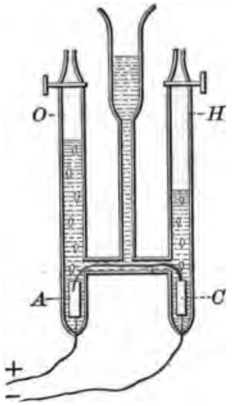


FIG. 381. — The electrolysis of water. The current flows through the water from the anode A to the cathode C.

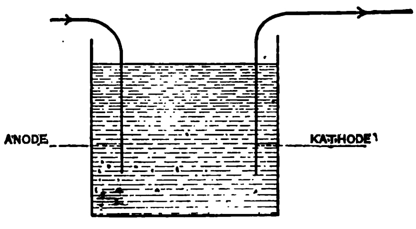


FIG. 382. — An electrolytic cell.

270. Electroplating and Electrotyping. — Electrolysis finds an important practical application in the coating of various objects with layers of metal, a process familiarly known as *electroplating*

and *electrotyping*. The object to be coated is used as the cathode of a circuit and is placed in the solution containing a compound of the metal to be deposited. If the anode is also made of this metal, it gradually dissolves as the current flows and supplies the place in the solution of the metal that is deposited by electrolysis on the cathode. This process is technically known as *electroplating*. Instead of printing books and cuts directly from the type or wooden plates, an impression of these may be made in a suitable material, and the mold thus formed, after it has been covered with a good conductor, may be used as the cathode of an electric circuit, and a deposit of copper made upon it by electrolysis, as is done in electroplating. After the layer of copper is of sufficient thickness, about that of ordinary tin plate, the electrolysis is stopped, the copper is backed up with lead or type metal, and then removed from the mold. Evidently the copper will now be an exact reproduction of the type which formed the mold, and from it, after being made of proper thickness, the pages of a book can be printed.

271. **The Storage Cell.** — When a current is sent through certain liquids, the electrolysis which takes place so changes the character of the anode and cathode as regards their chemical nature that they can afterward be used as the two plates of a voltaic cell. Thus Planté found that a current sent through a cell consisting of two plates of lead, placed near to each other in dilute sulphuric acid, so changed the plates of lead that, when the original source of current is withdrawn and the lead plates connected by an external conductor, a current flows through this conductor in the opposite direction to the original current. A cell used in this manner is called a *secondary* or *storage cell*. The commonest of the many forms, a modification of Planté's original, consist of two lead grids, into the interstices of which is pressed a paste of lead sulphate, immersed in sulphuric acid of a specific gravity of about 1.18 (Fig. 383). The electromotive force of this cell is about 2 volts, until nearly

discharged, and its resistance is small. It is customary to sp. . of a storage cell as being "charged" or "discharged," as though it were actually a storehouse of electric energy. The true conception, however, is that the so-called "charging" of a cell consists in converting the electrical energy of a dynamo into chemical energy, and the "discharging" is, just as it is in the ordinary voltaic cell, the conversion of chemical into electrical energy. The most important difference between the ordinary voltaic and the storage cell is that the latter is reversible, whereas the former is not. Their chief value is in those cases where a dynamo cannot be used directly, as in electric automobiles, and also as a sort of reserve power in connection with electric car or lighting systems in the rush hours, when the load would be too heavy for the unaided dynamos.

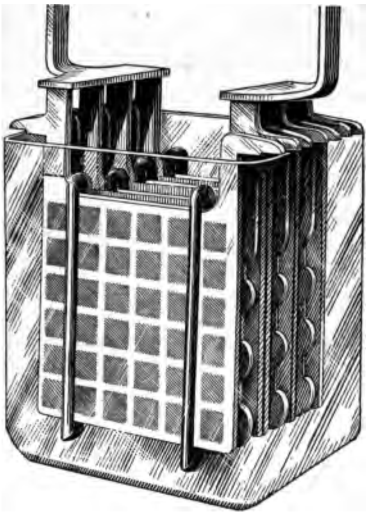
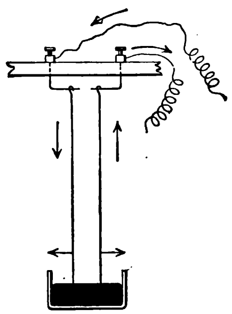


FIG 383. — The ordinary form of storage cell.

272. **Action of Currents upon Each Other.** — If two wires (Fig. 384) are freely suspended from two separate metallic supports, with their lower ends dipping into a cup of mercury, and a fairly strong current sent through the wires, they will repel each other. But when both wires are suspended from the same support, as shown in Figure 385, then the current flowing from the mercury will divide, part going through each wire, and the wires will move toward each other. These experiments show (1) that currents flowing parallel to each other and in opposite directions repel, (2) that cur-

rents flowing parallel and in the same direction attract each other. Currents flowing through wires which are near to each



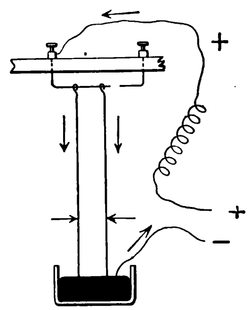


FIG. 384.—The currents repel each other. FIG. 385.—The currents attract each other.

other, but not parallel, act upon each other in such a way that if the wires can move, they will become parallel with the currents flowing in the same direction. Thus, in Figure 386, angles M and O would become smaller and angles N and P increase up to 180°. These actions of currents upon each other are helpful in our study of the electric motor. They can be better understood by recalling the fact that around each wire carrying a current there is a magnetic field, and those magnetic fields are responsible for the attraction or repulsion between the wires. When the wires are parallel and the currents in the same direction, the lines of magnetic force around the wires are as shown for A and B (Fig. 387). In this case the lines from A which go around B have the same direction as those which belong to B itself, and the wires move so that each wire may be brought within as many magnetic lines or as strong a magnetic field as possible, that is, they move toward each other. On the other hand, when the currents are parallel and opposite in direction, as C and D

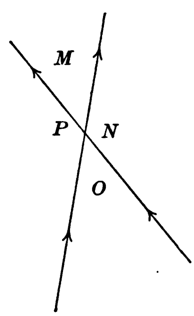


FIG. 386.—The currents act upon each other in such a way as to close the angles M and O.

(Fig. 388), the magnetic lines due to the field of C which include or, if sufficiently near, would include the wire D are opposite in direction to those of D itself, and similarly the

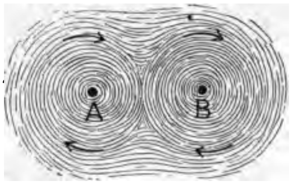


FIG. 387.—A and B are the cross sections of two parallel wires which have currents flowing in the same direction.

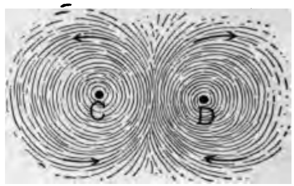


FIG. 388.—C and D are the cross sections of two parallel wires which have currents flowing in opposite directions.

lines of force of D which pass around C are opposite to those of C, hence the wires again move so as to make the magnetic fields as strong as possible, that is, each will move away from the opposing field of the other.

QUESTIONS AND PROBLEMS

1. What is the meaning of the terms *anode, cathode,* and *ions?*
2. If a compound containing a metal undergoes electrolysis, does the metal appear at the anode or cathode?
3. If two copper plates used as the anode and cathode respectively are placed in a solution of copper sulphate, what change in their weights would occur?
4. From this how could you tell the direction of the current?
5. Why does the electric bell not ring unless the push button is pressed upon?
6. Why does it not give a single tap for each push as the telegraph sounder does?
7. Explain why the carbon filaments in the glow lamp are placed in a vacuum.
8. Why must the current be carried through the walls of the bulb by means of platinum wires?
9. Why is a storage cell a more expensive source of currents than is a dynamo?
10. Would the currents in the neighboring turns of an electromagnet attract or repel each other? Why?

ELECTRICAL QUANTITIES AND UNITS

273. Strength or Intensity of a Current. — The strength of the water current in a river or a pipe is said to be known if we find the quantity of water which flows under a bridge or past a cross section of the stream in one unit of time. For example, the strength of the current in the pipe (Fig. 389) may be found by measuring, in any way, the number of pounds or gallons of water which flow past the cross section AB in one second. From this it is evident that the expression *strength of the current* means not the amount of energy of the current, but the amount of water conveyed by the flow. As shown in the discussion of work and energy, the amount of work which falling water can do depends upon the difference in level through which it may fall as well as the quantity of water falling. Also, the amount of work which a current of water can do in flowing between two points in a pipe depends upon the difference in pressure between those points, as well as the quantity of water flowing between them.

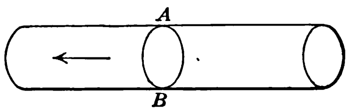


FIG. 389. — The circle AB is an ideal section across a pipe.

In a similar manner the *strength or intensity of an electric current means the number of units of electricity* (see section 239) *which the current transmits past a cross section of the conductor in a unit of time.* Here, too, the term *current strength* must not be taken to mean current energy. The *energy* or work done by the current depends upon both the *quantity of electricity* transmitted and the *difference in potential* or electrical pressure of the points between which the current flows (sec. 280).

274. The Practical Unit of Current Strength; the Ampere. — Since electric currents cannot be observed directly, in order to measure current strength it is necessary to select some one of the various effects of currents, such as their magnetic or chemical

action, in terms of which we may define a ***unit current***, that is, a current by means of which all others may be measured.

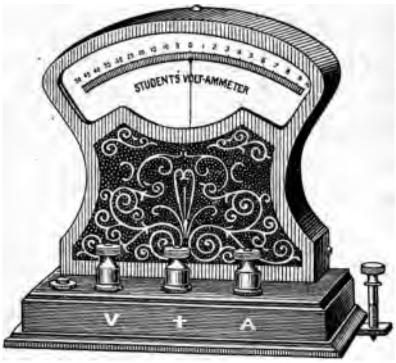


FIG. 390. — A combined ammeter and voltmeter.

That effect of currents which is most satisfactory for the purpose of establishing a fundamental unit is the chemical effect of electrolysis. The unit current based on this action is called the *ampere*, so named in honor of M. Ampère, a distinguished French physicist who made most important discoveries in connection with the effects of electric currents.

The legal definition of the ampere, by act of Congress, is "*the practical equivalent of the unvarying current, which, when passed through a solution of nitrate of silver in water (in accordance with standard specifications), deposits silver at the rate of* .001118 *gm. per second.*" The same current would deposit about .0003287 gm. of copper in one second. The quantity of electricity transmitted by one ampere in one second is called one *coulomb*, so named in honor of a French physicist, who first determined the laws of attraction and repulsion of electrified bodies.

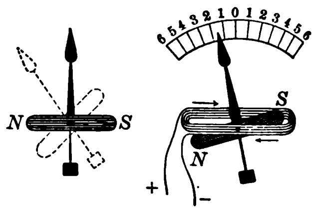


FIG. 391. — Showing the coil and magnet of the simple form of voltammeter.

For common use the action of the current on a magnet affords a much more convenient method of measuring current strength than the chemical action or electrolysis in terms of which the ampere is defined. Instruments constructed for the purpose of measuring current strength directly in amperes are

called *ammeters* (am(pere)meters). They are essentially galvanometers with short thick coils having very small resistance, so as to waste but little of the current passing through them. Ammeters are so graduated that the deflection of a pointer indicates directly on a scale the number of units or amperes of current passing through the circuit in which they are placed. A simple form is shown in Figures 390 and 391. In the more elaborate instruments the magnet is fixed and the coil moves as it does in the d'Arsonval galvanometer (Fig. 392).

FIG. 392. — Weston's ammeter.

275. Resistance; Conductance. — As already stated, no substance is a perfect conductor. This means that in the transmission of electric energy the conductor is always transforming a portion of the energy into some other form, usually heat. We may express this fact concerning the conductor by saying that it has *resistance.*

It can be shown experimentally that the resistance of conductors depend upon four factors:

1. *Other things being the same, the amount of resistance depends upon the material of which the conductor is composed.* For example, the metal silver has the least resistance of all substances; copper, a resistance slightly greater (see table, page 363).

2. *Other things remaining unchanged, the resistance varies directly as the length of the conductor.* Thus a given wire 6 ft. long has twice as much resistance as a piece of the same wire 3 ft. long.

3. *Other things remaining unchanged, the resistance varies*

inversely as the area of the cross section[1] *of the conductor;* or, *for cylindrical wires, inversely as the square of the diameter.* For example, a copper wire 1 mm. in diameter has four times the resistance of an equal length of copper wire having a diameter of 2 mm. (see table, page 393).

4. *The resistance of a conductor changes with its change in temperature.* The resistance of metals increases with their temperature, but the resistance of carbon and of all electrolytes, or substances which undergo chemical change, decreases with an increase of temperature.

The term *conductance* is sometimes used as the inverse or reciprocal of the resistance. In this sense, then, a substance with small resistance has a high conductance.

276. The Practical Unit of Resistance; the Ohm. — The resistance of any substance can be measured directly only by comparing it to the resistance of another substance taken as a standard. The unit selected for this purpose is *the resistance at 0° C of a column of mercury, 106.3 cm. long, having a cross section of about 1 sq. mm.* (strictly having a uniform cross section and a weight of 14.4521 gm.). This resistance, called the *standard ohm,* was selected by international agreement and has also been legalized by Act of Congress. It will be noted in the definition of the ohm that we fix (1) the substance, (2) the length, (3) the cross section, and (4) the temperature — the four things upon which the resistance of a conductor depends. The unit of resistance was named in honor of a German physicist, Georg Ohm, who experimentally established the laws of resistance.

The conductance of a body which has 1 ohm resistance is taken as a unit conductance, sometimes called 1 *mho.* Since the resistance of a conductor is the reciprocal of its conductance,

[1] The expression area of the cross section of the conductor means the area of the surface exposed by cutting the conductor at right angles to the current direction, whatever that may be.

$$\text{number of mhos} = \frac{1}{\text{number of ohms}}.$$

The relative resistances of a few common metals are shown approximately in the following table, silver, the best conductor, being taken as the standard:

RELATIVE RESISTANCE OF METALLIC WIRES OF THE SAME SECTION AT 0° C. SILVER IS TAKEN AS THE STANDARD. (FROM THE SMITHSONIAN TABLES.)

Silver	1.00	Platinum	6.13
Copper	1.08	Iron	6.63
Aluminum	1.98	German Silver	14.38
Zinc	3.84	Mercury	64.44

QUESTIONS AND PROBLEMS

1. If 1000 ft. of no. 18 copper wire has a resistance of 6.5 ohms, what will be the resistance of 88 ft. of the same wire?
2. A copper and an iron wire have the same length and the same resistance. Which has the larger section? How many times as large?
3. How must two or more wires be connected so that the total resistance is the sum of their separate resistances? How arranged so that the total conductance is the sum of their conductances?
4. Three wires having a resistance of 3, 6, and 9 ohms respectively, are connected end to end. What is their joint resistance? Their joint conductance?
5. A column of mercury 1250 cm. long has a cross section of 4 sq. mm. From the definition of the ohm and the laws of resistance, determine the resistance of the mercury column at 0° C.
6. Why does a galvanometer, in the circuit of a cell, show a stronger current when the plates are moved nearer to each other?
7. What is the effect on the current strength when the plates of a cell are lifted partly out of the fluid? Why?

277. Resistance Boxes; Rheostats. — Certain coils of wire, the resistances of which have been determined by the manufacturer and marked in ohms upon the coils themselves, are sold as standards of resistance. A number of such coils, arranged in a box for protection, is called a *resistance* box, or *rheostat.* The

wires are wound double (Fig. 393) to neutralize induction (see section 289). The two ends of each coil are connected to separate blocks of metal (A, B, C) placed near to each other on

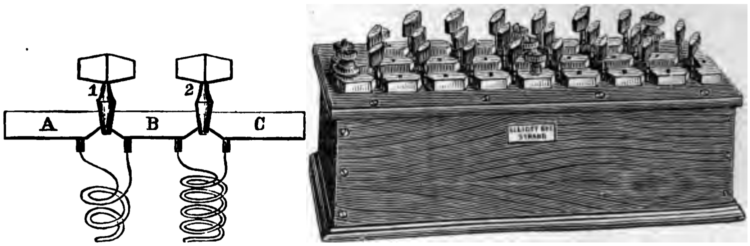


FIG. 393. — Resistance box, showing method of winding coils.

the top of the box as shown in Figure 393. The thick metal plugs (1, 2) placed between the blocks transmit the current directly from block to block without any appreciable resistance. The withdrawal of any plug compels the current to flow through the coil, hence introduces into the circuit the resistance of the coil which connects any two adjacent blocks of metal, as A and B shown in Figure 393. The withdrawal of two or more plugs introduces the sum of all the resistances of the coils which are thereby included in the circuit. In this way any amount of resistance can be introduced from that of the smallest coil up to the sum of all.

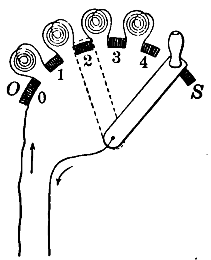


FIG. 394. — The plan of a motor starter or controller.

In the operation of trolley car and other motors a form of rheostat is used, called a controller, a simplified plan of which is shown in Figure 394. When the movable handle is in contact with S, the circuit is open and no current flows. If the controller handle is turned to block 4, the resistance of all the coils is in the circuit, hence we have, as desired, the weakest current at the starting of the motor. The handle is then moved in turn to blocks, 3, 2, 1, and 0, the resistance being

thus gradually cut out, according to the judgment of the operator, as the motor gains speed. A sudden starting of a car is not only unpleasant for the passengers, but also it may injure the motor. A motor at rest or moving slowly permits more current to pass through it than the same motor does when in rapid motion (see section 295). Hence if an extra resistance were not included in the circuit at the start and then gradually withdrawn, the current would be either too strong for the safety of the starting motor, or it would become too weak after the motor had gained speed.

278. The Practical Unit of Electromotive Force; the Volt. — We have had frequent occasion to speak of the difference in potential which must exist between two bodies, for example, the two poles or electrodes of a cell, in order to have a current in the external conductor between them. It has been suggested that this difference in potential may be measured in a manner similar to that in which differences in temperature or differences in water pressure may be measured. Since the practical unit of potential difference, or E. M. F., is based upon the understanding of the ohm and the ampere, it was not possible to define this unit clearly until the other two had been studied. *The unit E. M. F., called the volt, is the potential difference required to transmit a current of* 1 *ampere through a conductor which has a resistance of* 1 *ohm.* This unit was also adopted by international agreement and has been legalized by Act of Congress. It was named in honor of Count Volta, an eminent Italian physicist, who constructed the first electric cell.

A Daniell cell on open circuit has an E. M. F. of about 1.07 volts; some other single cells may have a voltage of 2 or slightly more.

In the direct current incandescent lamp system the difference of potential at the terminals of the dynamo is commonly about 110 volts.

In a trolley system the voltage is about 550, while in

arc light and power transmission it may reach 20,000 volts or more. The difference of potential in those cases where sparks several inches long are produced is very large, running up into the millions of volts.

279. The Voltmeter. — Any instrument so constructed that it will indicate the difference in potential directly in volts or the E. M. F. between any two points is called a *voltmeter*.

Fig. 395. — A voltmeter.

The voltmeter is practically a galvanometer with a very long coil of fine wire, hence having a resistance so high that scarcely any current is transmitted by it. These conditions are just the opposite of those which exist in the ammeter.

The principle of the d'Arsonval galvanometer (sec. 261) is used in high-class voltmeters, also in some ammeters, the deflection of the coil being indicated by a pointer moving over a scale graduated in volts (Fig. 395).

280. The Work done by a Current. The Heat generated in a Conductor. — An electric current may do work of various kinds. The external work may be magnetic, chemical, or mechanical, but the internal work consists in the production of heat in the conductor.

The amount of work done by a current, that is, the amount of energy transformed, depends upon (1) the quantity of electricity transmitted, and (2) the difference in the potentials of the points between which the electricity is transmitted. In practical units,

$$\text{work} = \text{coulombs} \times \text{volts}.$$

But when 1 coulomb is transmitted between two points hav-

ing 1 volt difference in potential, the **work** done is 1 joule (10,000,000 ergs), hence,

$$\text{no. joules} = \text{no. coulombs} \times \text{no. volts.}$$

On account of resistance some internal work is always done, and when no external work is done, all the energy of the current is converted into heat in the different parts of the circuit. Joule found that the number of heat units developed within a conductor varies (1) directly as its resistance, (2) directly as the square of the current strength, and (3) directly as the time the current continues. It has been proved experimentally that a current of 1 ampere flowing through a conductor having a resistance of 1 ohm generates in the conductor .24 of a calorie per second. Hence the number of calories produced by any current in any time can be found by the following:

$$\text{no. cal.} = .24\ (\text{no. amp.})^2 \times \text{no. ohms} \times \text{no. secs.}$$

or $$H = .24\ C^2Rt.$$

281. **The Power of a Current.** — The power of any agent has already been defined as its time rate of doing work; that is, the power of the agent is determined by the amount of energy it can transform in a unit of time. *An electric current which can do 1 joule of work in one second has a power of 1 watt* (see section 76). Hence a current of 1 ampere has a power of 1 watt when the potential difference of the points between which it flows is 1 volt. For most practical purposes the larger unit of power, the kilowatt (k.w.), 1000 watts, is generally used. The price of electric energy is usually estimated in watt hours or in kilowatt hours. A *watt hour* means the amount of energy expended or the work done in an hour by a current which has a power of one watt.

The power of any electric current can be expressed thus:

$$\text{no. watts} = \text{no. amps.} \times \text{no. volts,}$$

and the total energy used in a given time thus:

$$\text{no. watt hours} = \text{amperes} \times \text{volts} \times \text{hours.}$$

For example, if a 16 candle-power lamp on a 110 volt circuit has a current of .5 ampere, the power required will then be .5 × 110 = 55 watts. If such a lamp is in service for 10 hours, the electric energy transformed will be 550 watt hours. Certain instruments called *wattmeters* are designed to measure the *power* of a current directly.

Questions and Problems

1. What condition is necessary to produce a current of water between two points? A current of electricity? May you have either of these conditions and yet have no current? Give the reason in each case.
2. Does the current strength depend upon the amount of electricity transmitted in a unit of time or the amount of energy the electricity has? Compare with a current of water.
3. Upon what effect of an electric current is based the standard unit of current strength? Give the name and value of the unit current.
4. Other things being the same, would the current strength between the two poles of a cell increase or decrease with an increase in the conductance of the connecting wire? With an increase of the resistance of the wire?
5. Name and define the unit of resistance; the unit of conductance. A substance which has 3 units of resistance will have what conductance?
6. What is the P. D. or the E. M. F. required to send a current of 1 ampere through a conductor having 1 ohm resistance? What is the power of the current?
7. If the resistance were less than 1 ohm, would an E. M. F. of 1 volt give more or less than 1 ampere of current?
8. If the E. M. F. were more than 1 volt would it produce more or less than 1 ampere through 1 ohm? Would the power be more or less than 1 watt?
9. Under what conditions can a current of 1 ampere do 1 joule of work in 1 sec.? Give the meaning of a watt? of a kilowatt? of a kilowatt hour?
10. Express a kilowatt in horse power? A horse power in kilowatts?
11. An arc light has a current of 10 amperes, and a potential difference of 60 volts between the carbon points. Find (*a*) the power required to run the lamp, (*b*) the candle power counting 1 watt per candle power, (*c*) the cost per hour of running the lamp at 6 c. per kilowatt hour.
12. How much heat is developed in a wire having a resistance of 1.5 ohms by carrying a current of 12 amperes for 5 min.?

Ohm's Law and its Applications

282. Ohm's Law. — We have seen that the strength of the *current* between two points increases (1) when the *E. M. F.* between them increases, and (2) when the *resistance* of the conductor between them decreases. The exact relation between these three quantities, current strength, E. M. F., and resistance, was discovered by Dr. Georg S. Ohm, and hence the law which expresses this relation is named in his honor.

Ohm's law: *The current strength is equal to the electromotive force divided by the resistance,*

or in practical units, $\text{no. amperes} = \frac{\text{no. volts}}{\text{no. ohms}}$.

According to Ohm's law the number of amperes or the current strength may be increased in two ways, (1) by increasing the number of volts, or (2) by decreasing the number of ohms. The relations shown by Ohm's law are of great value in connection with the construction and working of cells, dynamos, and electrical apparatus generally. If any two of the three factors in Ohm's law are known, we can readily compute the third. For example, the E. M. F. of a trolley wire is about 550 volts, but the current strength through a trolley pole and a motor of a car to the earth depends also upon the resistance between those points. Similarly, the strength of the current passing through a person touching the trolley wire depends upon the resistance offered by his body and the other objects between him and the earth, as well as upon the voltage of the wire. For, as was shown, the power of a current in any case is found by multiplying the volts by the amperes.

283. An Application of Ohm's Law to the Voltaic Cell; the Grouping of Cells. — Since the voltaic cell or battery is designed to produce a current, it is evident, from Ohm's law, that the

strength of the current or the number of amperes furnished by any battery depends upon its E. M. F. and the entire resistance of the circuit through which the current passes. Because E. M. F. depends only upon the nature of the materials used in its construction, a large cell of a given kind has the same E. M. F. or voltage as a small one of the same kind. But on account of the larger cross section of the liquid conductor, the resistance of a large cell, called *internal* resistance, is less than the resistance of a small cell of the same kind. Cells are always used in connection with an external conductor, hence the entire resistance in the circuit is the sum of this *external* resistance and the internal or cell resistance. Ohm's law may then be expressed as follows:

$$\text{no. amps.} = \frac{\text{no. volts}}{\text{no. ohms (ex.)} + \text{no. ohms (in.)}}.$$

The number of volts produced by a battery may be multiplied by joining a number of cells, the positive pole of each cell being connected to the negative of the next, and the main external conductor being placed between the positive and negative poles of any two cells of the group (Fig. 396).

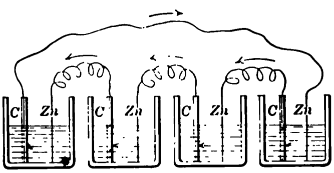


FIG. 396. – Cells arranged in series.

If four cells are connected thus, the electromotive force of the battery is four times as much as that of a single cell, but, since the whole current must pass through each cell, the liquid conductor is four times as long as it is in one cell, and the total internal resistance in circuit is also four times as great as in a single cell. If these four cells thus connected are now used in a circuit where the *internal resistance* is a small part of the total resistance, this increase in the internal resistance is of small consequence and the cells so connected give nearly four times the current strength of one cell. But when the external resistance

is very small, connecting the cells in this manner, and thus multiplying the internal resistance by four, is practically multiplying the total resistance by four, hence the gain which comes from the multiplied E. M. F. is nearly all neutralized by the increased resistance. This method of connecting cells, called *series grouping, is therefore best suited for use with a relatively large external resistance.*

Another method of grouping cells is shown in Figure 397. Here all the carbons or positive poles are connected to one end of the external conductor and all the zincs to the other end. All the carbons have a like potential and all the zincs are also at the same potential, though differing from the carbons, hence, connecting the plates in this way is virtually the same as using one cell with plates four times as large as those of one cell. It follows that the difference of potential between the two sets of plates, or the E. M. F. of the group, will be the same as if a single cell were used. But the internal resistance of the battery, because the total cross section of the liquid conductor is four times as large, will be only $\frac{1}{4}$ as great as the resistance of a single cell. The effect upon the current strength produced by this decrease in the internal resistance depends upon the relation between the internal and the external resistances. When the internal is the chief resistance in the circuit, a great gain is secured by decreasing it, and the four cells grouped in this way furnish a current strength nearly four times as great as that produced by a single cell. But when the internal is a small part of the total resistance, four cells arranged thus give little more current than a single cell. This arrangement of cells, called *parallel grouping, is valuable, therefore, when the external resistance is relatively small.*

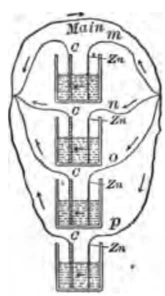


FIG. 397.—Cells arranged in parallel.

284. The Divided Circuit. — If the current which flows from the carbon to the zinc (Fig. 398) has two conductors or paths, M and N, offered to it between the points A and B, a part of the current will go through each conductor. This joint use of conductors M and N constitutes what is called a divided circuit between A and B. It can be shown experimentally that the current strength, or number of amperes, is the same between any two points in the circuit as it is between any other two points, hence conductors M and N jointly have the same current strength as either CA or Zn has separately. Between A and B the current divides into two parts which are in direct proportion to the conductances, or inversely as the resistances of wires M and N. Thus if wire M has one mho conductance or one ohm resistance and wire N has $\frac{1}{2}$ mho of conductance or 2 ohms resistance, wire M will have two of the three parts or $\frac{2}{3}$ and wire N one part or $\frac{1}{3}$ of the total number of amperes of current in the circuit. No matter how much the wires may differ in resistance or how many wires may be placed between A and B, each will have a share of the current, and the shares are directly proportional to the conductances of the wires or inversely proportional to their resistances. Either of the wires M or N in Figure 398 is frequently called a *shunt* to the other. A shunt is any one of the conductors in a divided circuit.

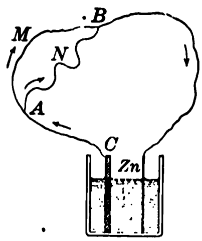


FIG. 398.—A divided circuit. Wire N may be considered as a shunt to M or *vice versa*.

A familiar example of a divided circuit is found in the method of wiring a building for the ordinary incandescent lights. Two main wires, one positive and one negative, are run side by side through a room of a building and between these two wires lamps are connected as shown in Figure 399. If each lamp has a current of $\frac{1}{2}$ ampere, the four lamps and the mains have a current of 2 amperes. The more lamps introduced

the less is the total resistance of the conductors between the main wires, and hence the stronger becomes the current which flows between them, provided the E. M. F. is constant.

285. Fall of Potential along a Wire. The Drop.—If the difference in potential between the points A and D (Fig. 400) is 1 volt, D having the lower potential, when the circuit is closed an experimental test of the connecting wire shows that the potential at point B is lower than the potential at A; at C it is lower than at B, and at D lower than at C. If the resistance of the wire is uniform, the potential falls uniformly from A to D; consequently at X, the middle point of the wire, it has fallen half of the difference between A and D, in this case $\frac{1}{2}$ volt below A. But if the resistance of the wire is not the same for each unit of length, then the potential falls more per centimeter of length in that part of the wire where the resistance is greater per cm. of length. Thus if the resistance between A and B were equal to the resistance from B to D, then the point B would be $\frac{1}{2}$ volt below A. This relation between fall of potential, sometimes called the *drop*, and the resistance of the conductor passed through explains why there is the same current strength in all parts of the same circuit. For, according to Ohm's law, the current strength between any two points is equal to their difference in potential or E. M. F. divided by the resistance between those points. Hence, if the E. M. F. falls along the wire at the same rate as the resistance is passed over,

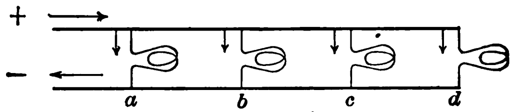


FIG. 399.—The total current between the two main wires is the sum of the currents in all the lamps.

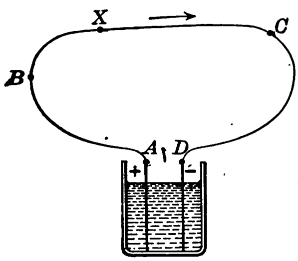


FIG. 400.—Fall of potential or the drop.

$\frac{E.M.F.}{R}$ is constant or the number of amperes between any two points in a circuit is the same as the number of amperes between any other two points in the same circuit. In the case of a divided circuit, the sum of all the currents in the branch circuits must be taken as shown in the preceding topic.

286. Wheatstone Bridge. — The principles involved in the divided circuit and in the fall of potential along a conductor enable us to understand the *Wheatstone bridge,* a familiar device for the measurement of electrical resistances.

A simple form of the bridge is shown in Figure 401. The heavy bands represent a frame of brass or copper bars so thick that their resistance may be neglected. This frame is broken or separated at four places. Into these intervals may be placed four conductors, R_1, R_2, R_3, and X, three of which have a known resistance, the fourth to be found. At the points B_1 and B_2 are attached the two wires from a battery, as shown, and a galvanometer is connected between G_1 and G_2.

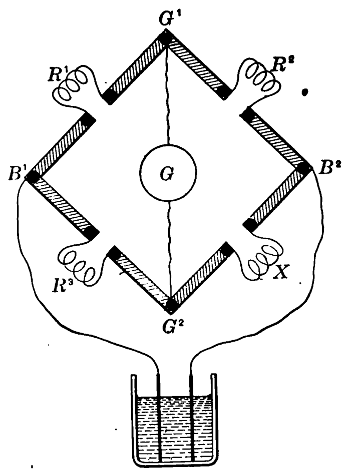


Fig. 401.—A simple form of Wheatstone's bridge.

The bridge is used as follows: A wire or any conductor, the resistance of which we wish to find, is introduced at X and the resistance in the rheostat R_3 is changed until we observe no deflection of the galvanometer. Since no current now flows between G_1 and G_2, in either direction, these points must be at the same potential. The current from B_1 to B_2 divides, part going by way of the lower and part by way of the upper branch of the bridge. According to the principles shown in the last

section, the total fall in potential from B_1 to B_2 must be the same by way of either branch; hence, when G_1 and G_2 are at the same potential, the resistance R_1 is then the same portion of the total resistance in the upper branch that R_2 is of the total resistance in the lower branch. From this it follows that $R_1 : R_2 :: R_3 : X$. The first three resistances being known, we may readily compute the value of the unknown resistance X.

Questions and Problems

1. State Ohm's law and give the meaning of each of the electrical terms used.

2. Find the current strength in a wire having 10 ohms resistance, when it connects the poles of a battery having an E. M. F. of 6 volts with closed circuit.

3. Find the E. M. F. required to produce a current of 10 amperes through a lamp which has a resistance of 12 ohms.

4. Find the resistance of a glow lamp which carries .5 ampere current when the P. D. is 110 volts.

5. What voltage is necessary to produce a current of 12 amperes in a conductor having .8 ohm resistance?

6. How much silver would 6 amperes set free from silver nitrate in 10 min.? If the resistance of the solution is 24 ohms what E. M. F. is required?

7. If a telegraph line has a resistance of 1 ohm per mile, find how many cells of an E. M. F. of 1.5 volts each are required to send a current of .2 ampere through a line 50 mi. long, neglecting the battery and instrument resistance. How would you group the cells? Why?

8. If 6 cells each having an E. M. F. of 2 volts and a resistance of 1.5 ohms are joined in series, find the total E. M. F. and the internal or battery resistance.

9. If the cells of the last problem are connected abreast or in parallel, find the total E. M. F. and the internal resistance.

10. Compute the current which each arrangement of the 6 cells would send through an external circuit of 90 ohms resistance, and determine which is the better arrangement. Compute the current by each arrangement for an external resistance of 2 ohms.

11. How many lamps in parallel, each having a resistance of 60 ohms and requiring a current of .4 ampere can be lighted by a battery or dynamo which has a power of 5000 watts, other resistances being neglected?

INDUCED E. M. F. AND INDUCED CURRENTS

287. **Electric Currents produced from Mechanical Energy by the Motion of a Conductor in a Magnetic Field.** — Thus far we have considered only one source of currents, that is, one kind of energy from which the energy of a current is produced. The source we have studied, under the general name voltaic cell, owes its energy to the chemical action which takes place between two substances, usually the metal zinc and some acid or salt. On account of the relatively high cost of energy furnished in this way, comparatively few applications of electric currents requiring much power were practicable, until a method had been discovered by which electric currents could be produced from the cheaper mechanical energy of the water wheel and the steam engine. In our study of the effects of electric currents, it was noted that a magnet can be moved by the action of the magnetic field which surrounds an electric current. It was also shown that a coil carrying a current can be moved by the action of a magnetic field as it is in the d'Arsonval galvanometer. In general, it was shown that mechanical motion can be produced from the energy of an electric current. About 1831 Henry in America and Faraday in England discovered, independently, that the process is reversible, and that energy in the form of an electric current can be produced by moving a conductor in a proper manner through a magnetic field.

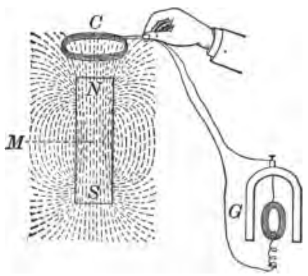


FIG. 402. — Currents are induced in the coil when it is moved so as to change the number of lines of force passing through it.

288. **Conditions under which Mechanical Motion produces Induced E. M. F. and Induced Currents.** — If a coil, consisting of a large number of turns of fine insulated wire (C, Fig. 402),

in the circuit of which is placed a d'Arsonval or other very sensitive galvanometer G, is thrust over one end of a strong permanent magnet (M, Fig. 402), or an electromagnet (Fig. 403), a current is produced in the coil. This current exists only while the coil is moving and is strongest when the motion is most rapid. If the coil is now thrust over the other end of the magnet with the same side of the coil foremost, a current is also produced, but the galvanometer shows that the current direction is opposite to that of the first.

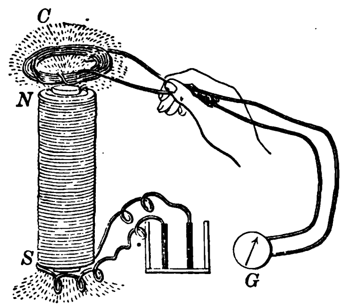


FIG. 403. — An electromagnet NS may be used to furnish the magnetic field.

A current thus produced by moving a conductor in a magnetic field is called an *induced current*, and the potential difference generated, which is the cause of the induced current, is known as *induced electromotive force* (*induced E. M. F.*).

By moving the coil in various directions through the magnetic field, it can be shown that a current is always induced in a closed coil when it, or the magnetic field, is moved in such a way as either to *increase or decrease* the intensity of the magnetic field within the coil, that is, change the number of lines of force passing through the coil. For example, when the coil (Fig. 402) is at the middle of the magnet, the number of lines of force or intensity of the field within the coil is as great as possible. Consequently, moving the coil toward either end decreases the number of lines within the coil and induces a current.

289. Other Methods of producing Induced E. M. F. and Induced Currents. — Let AB (Fig. 404) be a part of the circuit of a voltaic battery, which may be opened and closed at pleasure by means of the key K. Let CD be part of another complete circuit containing a very sensitive galvanometer G, but no battery. The wires AB and CD are supposed to be insulated,

but very near to each other. When the circuit is closed at *K*, thus starting the battery current in the direction *AB* and producing a magnetic field around the wire, the galvanometer shows an instantaneous current in the other circuit in the direction *DC*, that is, opposite to the direction of the battery current. If the battery current is now stopped, thus destroying the magnetic field around it, at that moment the galvanometer shows another instantaneous current in the other or galvanometer circuit, this time in the same direction as the battery current, that is, from *C* to *D*. The currents thus produced in the wire *CD* are induced currents, and the electromotive force in *CD* which produces these currents is induced E. M. F. The *conductor P* in which the original or primary current flows is called the *primary circuit*, and the conductor *S* in which the induced or secondary currents are produced is called the *secondary circuit.*

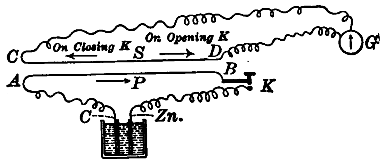


FIG. 404.—Currents are induced in *S* by the starting and stopping of the battery currents in *P*.

As long as the strength of the primary current is kept constant, its magnetic field undergoes no change, hence no currents will be induced in the secondary circuit; but any increase or decrease of the strength of the current in the primary circuit will produce a change in the magnetic field with the corresponding induced currents in the secondary circuit. Plainly, any variation of the current strength in the primary circuit produces a corresponding variation in the intensity of its magnetic field, hence induced currents are produced. It is evident that the induced E. M. F., hence the induced currents, will be increased as the lengths of the primary and secondary wires near each other are increased. This increase in length is most conveniently secured by winding insulated wires in the form of two separate cylindrical coils, one of which is large enough to admit

the other (Fig. 405). Either coil may be used as the primary or secondary circuit, though for experimental purposes it is usually desirable to use the larger coil as the secondary.

A third method of producing induced currents is readily shown by means of the coils just described (Fig. 405). Let us suppose the primary circuit to be permanently closed, and that it is being thrust quickly into the secondary coil. A galvanometer in the secondary circuit will show a current while the primary coil is entering the secondary. This induced current flows around the secondary in the opposite direction to the current in the primary coil. As long as the primary coil remains at rest, with a steady current in it, no current is induced; but a sudden withdrawal of the primary again produces an induced current in the secondary coil, this time flowing in the same direction as the primary current. It will be readily noted that this third method of inducing currents is essentially like the second, for moving a primary coil, bearing a current, toward or from the secondary, is practically the same as starting or stopping the current in a primary coil while it is motionless within the secondary coil. These three methods of inducing E. M. F. currents in a coil having a closed circuit may be briefly stated as follows:

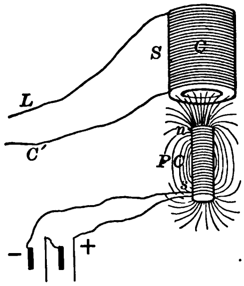


FIG. 405. — A primary coil *PC*, and a secondary coil *SC*.

(*1*) *Currents are induced in a closed circuit conductor by increasing or decreasing* (*stopping or starting*) *the strength of a current in another parallel conductor near it.*

(*2*) *Currents are induced in a closed circuit conductor by moving toward or from it another near-by parallel conductor bearing a current.*

(*3*) *Currents are induced in a closed circuit conductor by relative motion between it and a magnet in such a way that the number of lines of force included within the circuit increases or decreases.*

By recalling the fact that the magnetic field associated with a wire or a coil is like that around a magnet, all these methods may be summed up in this statement: *Electromotive force is induced and currents flow in any closed circuit conductor, when either the conductor or a magnetic field is so moved that the intensity of the magnetic field included within the circuit is either increased or decreased.*

290. **The Intensity of the Induced E. M. F.** — The intensity of the induced E. M. F. may be increased by making the secondary coil as long as possible and the intensity of the magnetic field which is produced and destroyed within it as great as possible. When a primary coil, is used, the insertion of a core of soft iron, on account of the permeability of the iron, greatly increases the intensity of the magnetic field, and consequently the intensity of the induced E. M. F. The time required for the conductor to cut the lines of magnetic force, or with a closed circuit the time required to produce or destroy the magnetic field within the secondary coil, is also a factor in the intensity of the induced E. M. F. Thus a given coil or magnet thrust into the secondary in $\frac{1}{10}$ of a second will produce an E. M. F. ten times as great as though a whole second were used to produce the same motion of the coil or magnet. Hence, as will appear later, an increase in the speed of a dynamo increases the E. M. F. of the machine.

291. **The Direction of the Induced Currents; Lenz's Law.** — If we first find the direction of the needle's deflection produced by a battery current of known direction going through a galvanometer, we may then determine the direction of any of the induced currents which the instrument is able to detect. If this is done, it is found that *the direction of the induced current is such that it always opposes the motion of the coil or magnet, and consequently of the magnetic field, that induces it* (Lenz's law). Recalling the laws of attraction and repulsion of parallel currents and of magnetic fields, we can readily make the appli-

cation of this law. When coils are approaching each other, repulsion between their magnetic fields hinders their motion, hence the direction of the induced current must be opposite to that of the primary current (Fig. 405). But when the primary coil is moving away from the secondary, attraction hinders this motion, hence the direction of the secondary current will now be the same as that of the primary. Because of these hindrances to their relative motion, it follows that the agent moving the coils and their magnetic fields, either toward or from each other, must do more work when producing these induced currents than would be required to move an equal mass of other material. This extra amount of work is the source of the energy of the induced currents.

Recalling the facts that stopping and starting the primary current, when the coils are relatively at rest, is equivalent to moving the primary coil, as above described, we can easily determine the direction of the induced currents in this case also. For in order that the magnetic field of the induced current may hinder that of the primary, the direction of the induced current must be opposite to that of the primary when the circuit is being closed, and the same as the primary when the circuit is being opened (Fig. 404).

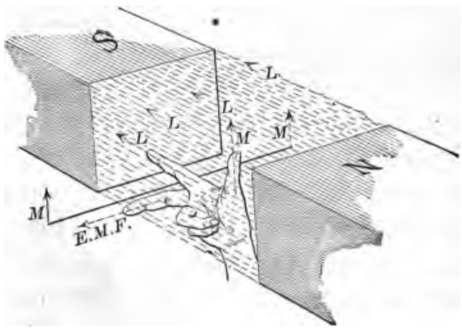


FIG. 406. — Fleming's, or the dynamo rule.

Fleming's Rule for finding the Direction of Induced Currents. — Let the index finger of the right hand point in the direction of the magnetic lines of force, the thumb at right angles to the finger point in the direction in which the conductor is being moved; then the second finger, held at right angles to both the index finger and the thumb, will point in the direction of the induced E. M. F. (Fig. 406). This is sometimes called the *dynamo rule*.

292. Dynamo-electric Machines. — Machines designed to transform mechanical energy into the energy of electrical currents are called dynamo-electric machines. They operate on the principle that moving a coil of insulated wire in such a way as to increase or decrease the number of lines of force passing through the coil induces currents in the coil. When the magnetic field used is produced by a permanent magnet, the machine is called a *magneto*, but when electromagnets are used to produce the field, the machine is called a *dynamo* or a *generator*.

293. Principles of the Magneto and Dynamo. — If a single straight wire is thrust inward across the lines of force between the poles of a permanent horseshoe magnet, as shown in Figure 407, there is an induced E. M. F. in the wire from *b* toward *a*, that is, the potential of *b* falls and that of *a* rises, as is the case with the two poles of a cell with an open circuit. While the wire is being withdrawn, the induced E. M. F. is from *a* toward *b*. (See Fleming's rule.) The circuit being open, there is no current in either of these cases. If, however, a closed loop of wire or coil with a single turn were thrust between the poles of the same magnet, by the same line of reasoning, it is plain that the E. M. F. would be induced in the same direction in both branches of the loop. These would oppose each other, hence produce no current around the coil as a whole. Upon withdrawing the loop, the induced E. M. F., though opposite to that produced at entrance is in the same direction in both branches, and again there is no current around the circuit of the loop. That is, when both branches of a coil cut across the same number of lines of force in the same direction, though E. M. F. is induced in the parts, a current is not gener-

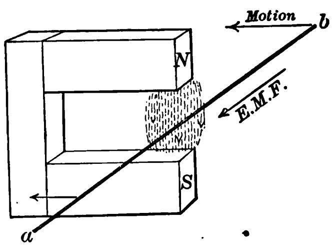


FIG. 407. — The conductor *ab* is being moved inward across the lines of force.

ated in the coil as a whole because the E. M. F. in one half opposes and neutralizes the E. M. F. in the other half of the coil. Let us now suppose that the loop is mounted on an axle $x\ y$ (Fig. 408) and rotated in the magnetic field between the poles. With this method of moving, it is plain that the upper half of the rotating loop always cuts the magnetic lines in a direction opposite to that in which the lower half is cutting them at that time. This is true without regard to the direction of rotation or to which half of the loop is uppermost. Let us suppose that the direction of rotation when observed from x is right hand or clockwise, then during the first half rotation, the direction of the induced E. M. F. is from b toward a in the upper branch and from d toward c in the other. In this case, the E. M. F. of the lower adds to the E. M. F. of the upper branch of the coil and a current flows around the coil in the direction *dcba*.

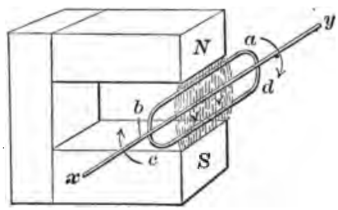


FIG. 408.—A loop is being rotated in the clockwise direction as seen from x.

During the second half rotation each half of the loop cuts the magnetic lines in the same direction as the other did in the first 180°, hence by similar reasoning there is now an induced E. M. F. and a current in the whole loop in the direction *abcd*. There are, therefore, two induced currents opposite in direction for each complete rotation of the closed loop circuit. But these currents expend all their energy in heating the wire through which they flow.

The Alternating Current.—Let us next suppose that the loop is cut between a and d. A rotation of the open loop still induces E. M. F. but no currents in its open circuit. In the first half of the right hand rotation, the potential of the d end of the loop falls, and that of the a end rises. An outside conductor connecting a and d would then

complete the circuit and a current would flow through it from a toward d. In the second half rotation, there is an induced E. M. F. from a toward d. This E. M. F., in so far as the particular ends of the loop of wire are concerned, is opposite to the one induced before, but it, like the first, is directed from the upper toward the lower end of the loop. An outside conductor connecting a and d would now have a current opposite to the one first produced. But how can we connect an outside conductor to the open loop? Let us next suppose that each end of the loop is attached to a metal ring which is insulated from the axle and from the other ring (R' and R'', Fig. 409), and that a strip of copper or carbon called a brush (B' and B'') presses continuously against each ring. We have shown how with each rotation there is an alternate rising and falling of the potentials of the rings and brushes attached to A and D, hence, if there is an external conductor connecting them, there are *currents in this conductor alternating in direction.* This loop of wire, rotating in a magnetic field, constitutes the simplest form of the magneto and dynamo.

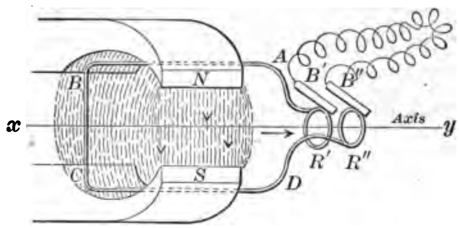


FIG. 409. — An alternating current. The top wire moves toward the observer.

The Direct Current. — If, however, each end of the open loop is connected to a half ring, or copper block, insulated from the axle and the other half ring, and the two brushes are arranged so that one of them is always in contact with the upper block and the other with the lower, then the current though alternating in the loop always flows in the *same direction in the outside conductor* (Fig. 410). For, as has been shown, with a given direction of rotation the induced E. M. F. is always in the same direction in that part of the coil which happens

to be above, hence the upper half ring always has the same relative potential, that is positive or negative, and the lower half the opposite potential. The attaching of the open ends of the loop to insulated half rings or blocks, or indeed *any device for converting the alternating currents of the loop into currents of a constant direction in the outside conductor, is known as a commutator.*

294. **The Dynamo.** — The magnetic field of a permanent magnet at the best is only moderately strong, hence, the magneto is rarely used except for the production of small currents suitable for such purposes as ringing bells.

In the *dynamo* we use the more intense magnetic field of an electromagnet. In addition the lines of force are concentrated by placing highly permeable soft iron within the coils between the field poles. This core rotates with the coils and the whole rotating portion of the machine is called the *armature*.

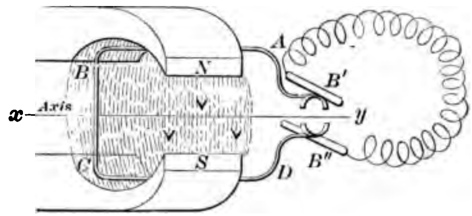


FIG. 410. — A direct current. The half rings and the brushes B', B'' constitute the commutator.

In our explanation of the general principles of the magneto and dynamo, we have for the sake of simplicity spoken of a single loop or coil. Of course, the single loop would give but a feeble current and that would disappear twice during each rotation. For when the lines of force are perpendicular to the plane of the loop, it might rotate through a considerable angle without producing any appreciable change in the number of lines of force passing through the loop. But if an armature is constructed by using many turns of insulated wire in each coil, and a number of such coils are so arranged around the axle that there is always one set cutting directly across the lines of magnetic force, the induced E. M. F. can be

greatly increased and, if the speed of rotation is sufficient, rendered practically constant. As the number of sets of coils is increased, the number of pairs of separate insulated blocks in the commutator will also have to be increased, but with a two-pole magnetic field, two brushes are sufficient. An armature constructed on this plan, known as the *drum armature*, is shown in Figure 411. By means of the commutator as already explained the alternating currents in the armature are converted into a current in one direction through the outside conductor, hence this type of machine is called a *direct current dynamo.*

In this type the current from the dynamo itself is used to intensify the magnetic field. Enough magnetism remains in the iron cores of the electromagnet to start the induction of a current when the armature begins to rotate. On account of the weak magnetic field this current is at first very weak. In some cases the entire induced current is then conducted from the positive to the negative brush through the wires of the field magnet as well as the rest of the outside circuit, or in other cases a part of the current is sent through the coil of the electromagnet and the remainder through the main circuit. In either case the current going through the electromagnet rapidly increases the magnetic field and in consequence the induced currents become stronger. Thus the direct current dynamo builds up its own magnetic field and in consequence its own current strength, as the armature gains in speed. When the whole of the induced current goes through the electromagnet or field coils the dynamo is said to be *series*

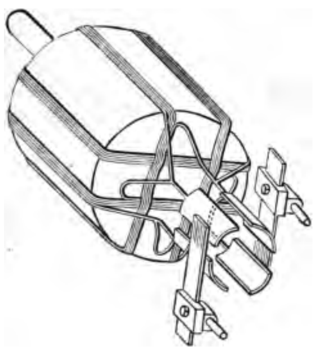


Fig. 411. — Method of winding coils of wire on a "drum" armature.

wound (Fig. 412), but when only a portion of it is used to produce the field the dynamo is said to be *shunt* wound (Fig. 413).

295. The Electric Motor.—It has been shown that the mechanical motion of the armature of a dynamo results in the production of an electric current, hence the purpose of the dynamo is to transform mechanical energy into the energy of an electric current. On the other hand, if a current from a battery or a dynamo is sent by way of the brushes through another direct current dynamo, its armature rotates and the energy of the electric current is thus converted into mechanical energy.

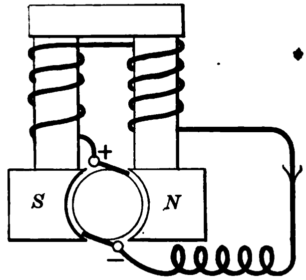


FIG. 412.—A series wound dynamo.

The manner in which a current going through an armature produces motion can be easily understood by recalling the action of the magnetic lines of the field magnet upon those of the armature as already stated for the D'Arsonval galvanometer. When a current is sent in the proper direction through the armature coil *ABCD* (Fig. 410), the field produced in the coil is opposite to that of the magnet *NS*. On this account there will be a repulsion between these fields, and the armature will rotate toward a position 180° from that shown. When the coil reaches this position, the fields would then coincide and the rotating action would cease, but at that time, by the action of the commutator, the current is reversed in the armature coil, though not in the field magnet, hence the fields again oppose and the coil is given another thrust forward. This same line of

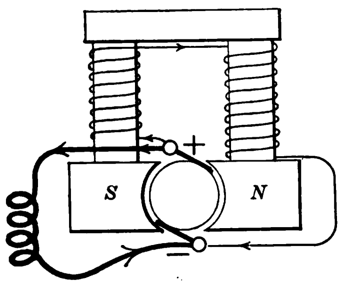


FIG. 413.—A shunt wound dynamo.

reasoning applies to each of the separate coils in the armature; hence there is always one coil in such a position that its magnetic field opposes that of the field magnet G, thus producing a continuous rotation.

A dynamo-electric machine *when used to produce mechanical from electrical energy is called a motor.* On this account in a trolley or other system where the electric energy is produced by one machine and transformed into mechanical motion by another of practically identical construction, the machine which produces the current is commonly called a *generator* and the one which produces the motion a *motor* (Fig. 410).

In a series wound machine the direction of rotation of the armature, when used as a motor, will be opposite to the direc-

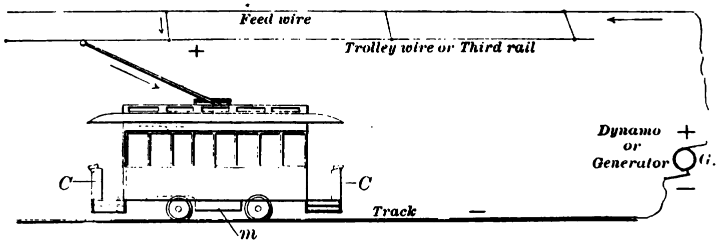


FIG. 414. — Showing the main features of a trolley system, the generator G, the controller C, and the motor m.

tion required, when used as a generator, to produce a current in the same direction. On this account a running motor generates in its armature an electromotive force, E. M. F., which is opposed to that of the current going through it. Hence when a motor has acquired a high speed, its *counter E. M. F.* permits comparatively little current to go through it. At the start, however, too strong a current might flow unless regulated by a rheostat, as already explained (sec. 277).

296. **The Alternator; Alternating Current Dynamo.** — The magneto gives an alternating current. If the permanent magnet of the magneto is replaced by an electromagnet the drawing (Fig. 409) would represent the simplest form of the *alternating*

current dynamo. With a single coil and two field poles the current would be reversed only twice for each revolution of the armature. In order to produce the desired high frequency of alternations, 50 to 120 per second, without excessive speed, it is necessary to multiply the number of coils in the armature as well as the number of poles in the field (Fig. 415). This makes the alternators complicated in structure. On account of the alternating character of its own current the field magnets of this type of dynamo must be magnetized by a separate direct current dynamo called the *exciter*.

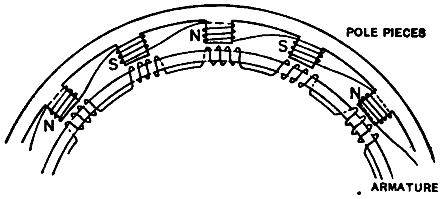


FIG. 415. — Diagram of winding in alternating current dynamo.

297. **The Induction Coil.** — Large, secondary coils of fine, well-insulated wire, surrounding primary coils having a soft iron core, are manufactured and sold under the name of *induction* or Ruhmkorff coils. Though essentially the same as the coils already described for producing induced currents, attention to

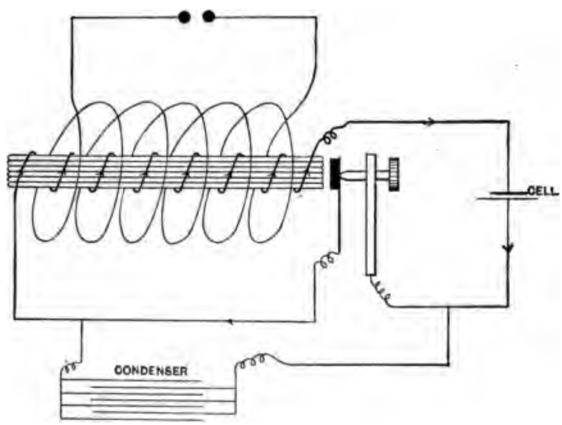


FIG. 416. — Diagram of induction coil.

such points as a quick automatic make and break, the addition of a condenser to facilitate the stopping of the primary current, and the use of a very large number of turns in the secondary coil make it possible to secure such a high difference in potential between the two terminals of the secondary coil that sparks many inches in length may be produced. A diagram of the parts of such a coil is shown in Figure 416.

298. The Transformer. — For economy of production and transmission alternating currents are commonly produced with an E. M. F. of 1000 to 5000 volts or more. Because such high potential currents are dangerous and also because they are not well suited for most uses, they must be lowered in potential before they are admitted to buildings. An apparatus designed to accomplish this change in potential is called a *transformer*. The principle of the transformer is that of the induction coil, as shown by the coil and magnet, already explained. The commercial form of the instrument is essentially the same as that shown in Figure 417. Around an iron ring are wound two separate thoroughly insulated coils containing a different number of turns. If the primary current alternates through B, the coil having the larger number of turns, the secondary coil A having the smaller number will furnish currents with a lower E. M. F. Thus if the primary coil has ten turns to every one in the secondary, the current will be lowered to $\frac{1}{10}$ its original voltage. This type is frequently called a *step-down* transformer. On the other hand, in long lines of transmission it frequently happens that the fall of potential or the drop is so great, at points distant from the generators, that a transformer must be used to raise the potential to the required amount. This type of transformer, known as a

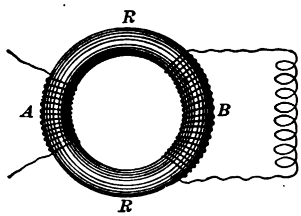


FIG. 417. — Diagram of transformer: two coils wound on an iron ring.

step-up transformer, acts in a manner opposite to that already described.

299. **The Telephone.** — The original Bell telephone, the part now used for a receiver only (shown in Fig. 418), consists (1) of a strong permanent magnet *A*, (2) a small coil of insulated wire *B* surrounding one end of the magnet, and (3) a thin sheet of soft iron called the diaphragm, *C*, placed very near but not in contact with the magnet and the coil. The whole is protected and supported by a hard rubber case.

Two such instruments, when connected by wires *M* and *N*, operate as follows: The sound waves from the speaker's voice throw the diaphragm at *C* into vibration, the frequency depending upon the pitch of the tone produced. When the vibrating diaphragm of *C* approaches the coil and magnet, the change thus produced in the magnetic field induces a current in the coil at *B* which flows around the entire circuit including the coil of *D*. This current, when flowing in the proper direction, increases the magnetic field of coil *D*, and the diaphragm *D* is consequently drawn nearer to the magnet. When the diaphragm *C* goes upward in its vibration another current is thereby induced, which this time flows oppositely around the circuit including the coil of *D*, hence weakens the field, and the diaphragm *D* goes upward. Thus the second diaphragm vibrates as many times per second as the first, and because it imitates the motion of the first *it sets up vibrations in the air and produces at D an imitation of the sound of the speaker's voice* at *C*.

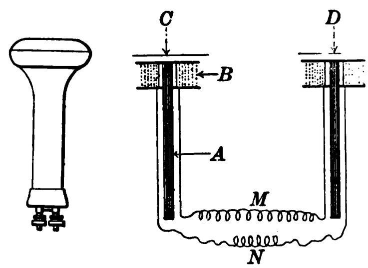


FIG. 418.—The original telephone, now used as a receiver only.

It will be noted that the telephone wire does not transmit sound waves but electric currents which correspond in

frequency to that of the sound waves. In the modern instrument a horseshoe instead of a bar magnet is used in the receiver, thus improving the results though not changing the principle. A different and more complex form of transmitter is also used, the principle of which, known as the microphone principle, is shown in Figure 419. On the back of a vibrating diaphragm, at the mouthpiece M, is a carbon button resting lightly against another piece of carbon C. The diaphragm, having the carbon button, is connected with one pole of a battery, the carbon C being connected with the other pole, by way of the line and the receiver R. If the diaphragm is not vibrating, the battery current flows steadily across the point of contact between the two carbons.

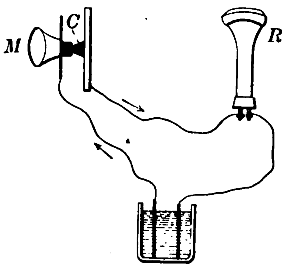


FIG. 419.—A simple microphone transmitter.

In 1878, Hughs discovered that the conductance at the point where two carbons *touch* each other is greatly increased by pressing the carbons together and vice versa. As the sound waves strike against the diaphragm D, they produce variations in the pressure of the carbon points against each other, hence the strength of the battery current will increase and decrease with each vibration of the diaphragm. These fluctuations in the current will produce a corresponding variation in the magnetic field of the receiver,

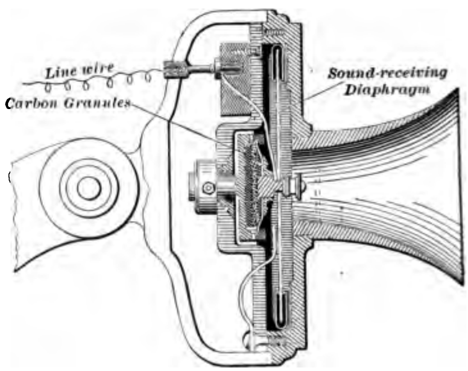


FIG. 420.—A modern long distance microphone transmitter.

hence they produce a vibration of the diaphragm of the receiver. Since these changes of strength of the battery current greatly exceed the total currents that can be induced by the method first described, this type, known as the microphone transmitter, makes long distance telephoning possible. In the more recent forms of the microphone transmitter, by the use

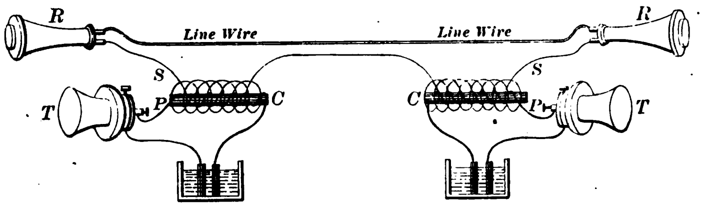


FIG. 421. — A telephone circuit, battery system.

of granulated carbon, the action of many carbon points is introduced and the results improved (Fig. 420). Another improvement consists in the addition of an induction coil. The current going through the microphone transmitter is sent through the primary *P* of the coil, and the induced higher potential currents of the secondary *S* are transmitted to *R*, the receiver of the person hearing (Fig. 421).

ELECTRIC CONSTANTS OF COPPER WIRE AT 0° C.

B & S GAUGE NUMBER	DIAMETER IN MILLIMETERS	OHMS PER METER	METERS PER OHM	CAPACITY IN AMPERES
0	8.251	.0003	3284.0	185.
5	4.621	.0010	1030.0	77.
10	2.588	.0031	323.1	32.
15	1.450	.0099	101.3	13.6
20	0.812	.0315	31.8	5.7
25	0.454	.1003	9.97	2.4
30	0.255	.3198	3.13	1.0
35	0.143	1.0194	0.98	0.4

XVII. SPECIAL FORMS OF ETHER WAVES AND RADIATIONS

300. Ether Wave or Wireless Telegraphy. — Much interest was aroused by the discovery, in 1888, of a method of producing and detecting electric waves. Hertz, their discoverer, showed that these electric waves were closely related to the waves which constitute light and so-called radiant heat, though they have a much greater wave length. Being ether waves, and the ether existing, as we believe, throughout all space, including that which exists between the molecules of even the densest matter, the idea of communicating or signaling by means of these electric or Hertz waves readily arose in the minds of many investigators, prominent among whom was Marconi. Many different systems of the so-called wireless telegraph have been invented and used, one of the simplest being Marconi's early form. All systems require, first, a wave generator, commonly called a *transmitter* or *emitter*, and second, a wave detector, which in the early form was called a *coherer*. The chief features of a simple set of apparatus suitable for short distances are shown in Figures 422 and 423.

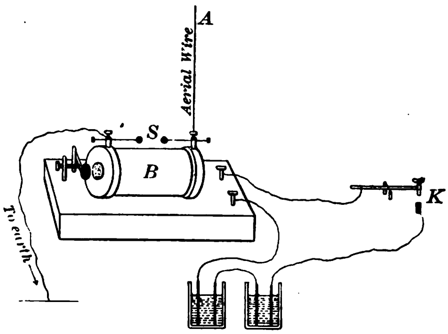


FIG. 422. — A simple apparatus for producing electric waves.

At the transmitting station an induction coil *B*, operated by a battery or dynamo, discharges or sparks across the gap *S*,

every time the primary circuit is closed by the key K. This high potential discharge, as in the discharge of the Leyden jar, sends out electric waves in the ether from the aerial wire A, which travel in all directions with the speed of light. A portion of each wave or set of waves will strike upon the aerial wire A' at the receiving station. Attached to the lower end of A' is the detector, in this case a coherer M. It consists of a glass tube about $\frac{1}{4}$ in. in diameter, into which are inserted two closely fitting metal plugs, p and p', with a small space

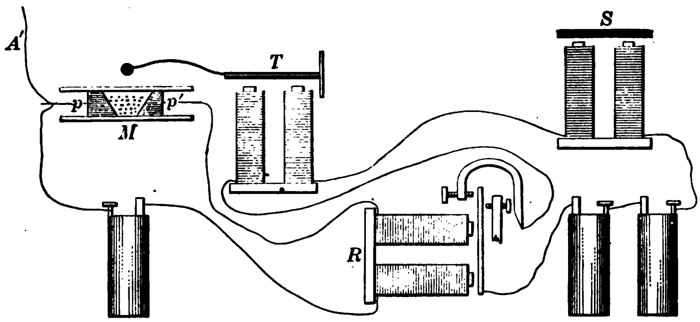


FIG. 423. — A simple apparatus for receiving electric waves.

between their ends about two thirds full of iron filings, or a mixture of iron, nickel, and silver filings M. The handles of these plugs are attached to the two poles of a single Leclanché cell, in the circuit of which is a relay R. Before the electric waves are received by the coherer, the metal filings have such a high resistance that practically no current flows through them, but the instant a wave passes through them, they become, for some reason not yet fully determined, highly conductive and a current then flows through the relay circuit. The relay then closes the circuit of another battery in which there is a sounder S, as in the ordinary telegraph. After the wave, or short train of waves, has passed a slight tap upon the coherer restores its high resistance and the relay current ceases, thus opening the sounder current. This restoring tap can be auto-

matically given to the coherer by the clapper of an electric bell T, included in a shunt of the same circuit as the sounder. Thus the coherer is made ready for the next set of waves. Of course, in the practical working of the system, each station or ship must be equipped with both a transmitting and a receiving apparatus. In order to produce the best results, both of these instruments are complicated in detail.

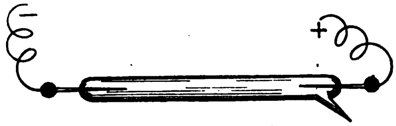


FIG. 424. — A "vacuum" tube.

301. Electric Discharges through Moderately Rarefied Gases; Geissler Tubes. — Let us suppose that the terminals of an induction coil are connected to two pieces of platinum (Fig. 424), sealed into the two ends of a long glass tube from which the air, or other gas, may be exhausted through a side tube. As the air within becomes less dense, the character of the spark, that is, the light emitted by the air as the discharge takes place through it, gradually changes. When the exhaustion reaches about $\frac{1}{300}$ or $\frac{1}{500}$ of the ordinary atmospheric pressure, the tube is filled with a brilliant glow, the character of which depends upon the kind of residual gas or vapor the tube contains, as well as the shape and kind of glass used in the construction of the tube. Such tubes, made in fancy shapes and permanently exhausted, are sold under the name of Geissler tubes (Fig. 425). Recently, tubes of this type have come into use for commercial lighting. The peculiar vibratory feature, as well as the stratification shown in some of these tubes, suggests that in them we may find an explanation of the remarkable atmospheric effects known as the Aurora.

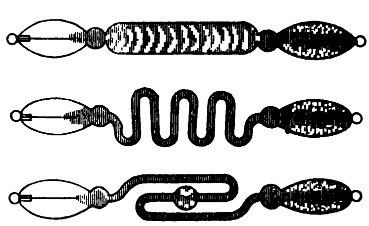


FIG 425. — Geissler tubes.

302. Electric Discharges through Very Highly Rarefied Gases;

Crookes Tubes and Cathode Rays. — If the exhaustion of a tube is carried to about one millionth of an atmosphere, the tube is now known as a Crookes tube, in honor of Sir William Crookes, who first produced these tubes in 1879. The discharge through such a tube is entirely different from that in a Geissler tube. Instead of producing a glow in the small amount of residual gas, there is now a stream of very minute particles, called *cathode rays*, projected perpendicularly from the negative terminal or cathode, as is shown by the shadow they produce (Fig. 426). These particles of negative electricity, or particles charged with negative electricity, are called *electrons* by some, by others *corpuscles*. They travel with an enormous velocity, probably as great as 100,000 miles per second. When the electrons strike upon any substance, they may produce heat, mechanical motion, a phosphorescent glow as on glass and precious stones, and, when they strike the dense substance platinum, their sudden stoppage results in the generation of X-rays. The stream of electrons or cathode rays is deflected by a magnet. It is also found that the flying electrons are able to penetrate, but with widely varying facility, such substances as wood, paper, and even thin sheets of aluminum. In this fact we have evidence that they are extremely minute. The present inferences regarding the nature of the electrons constituting the cathode rays, may be summed up as follows: (1) Each electron has or is a definite fixed charge of negative electricity, the same amount as is conveyed by each atom of matter in electrolysis. (2) Every electron has a definite and uniform mass which is probably about $\frac{1}{800}$ or $\frac{1}{1000}$ of the mass of a hydrogen atom. (3) Only one kind of electron can be obtained. (4) In

Fig. 426. — Cathode rays producing a shadow.

ordinary conduction as in a copper wire, electric currents are due to the locomotion of the electrons through the material of the conductor, they being passed along rapidly from atom to atom. In electrolysis the electrons travel slowly, in company with the more massive atom. In gases they travel much more rapidly, acquiring in highly rarefied gases nearly but not quite the velocity of light. (5) Whenever an electron is suddenly started, stopped, or made to change its direction, it produces an agitation in the ether, which process we commonly speak of as radiation.

303. **Röntgen or X-Rays.** — In experimenting with cathode rays in 1895, Röntgen of Germany discovered that when these rays or electrons struck upon the walls of the tube or upon a platinum plate inside, they produced a kind of radiation which was able to pass through the glass of the tube and such opaque bodies as wood, flesh, cardboard, and other denser bodies to a less degree. The exact nature of these rays, commonly known as X-rays, has not yet been determined. They cannot be reflected or refracted, as are the ordinary ether waves of light and radiant heat. Nor can they be deflected by the action of a magnet as are the cathode rays. They are not visible, but they fluoresce or generate light when they strike upon the walls of the tube, and especially when they fall upon a screen composed of platino-barium cyanide or calcium tungstate. They can be readily produced by a special form of tube shown in Figure 427, in which the cathode is concave, so

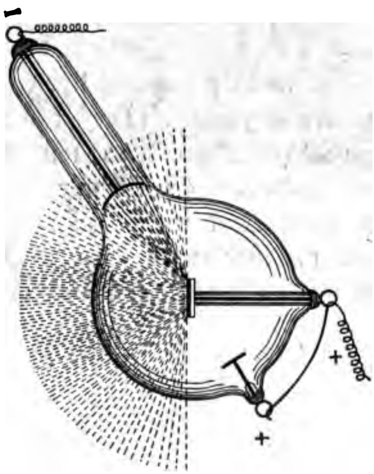


FIG. 427. — An X-ray tube.

that the stream of cathode rays strikes directly upon the platinum plate or anode arranged at an angle to the stream so that the rays generated pass out at one side of the tube. In the fact that X-rays act upon a photographic plate in much the same way that light acts, is found an important application of them. If the hand or any object composed of parts unequally permeable to these rays is placed in contact with the outside of a plate holder, the rays will produce upon the plate within, when properly developed, a kind of shadow photographic negative. Since the X-rays penetrate the bones less readily than they do the flesh, the outline of the bones is thus shown (Fig. 428).


Fig. 428. — Hand, as shown by an X-ray photograph.

304. Radio-activity; Radium. — In 1896, when experimenting upon the element uranium, Becquerel discovered that it spontaneously emitted rays which penetrated many opaque bodies, and acted upon a photographic plate in much the same manner as X-rays act. In honor of their discoverer, rays of this kind are known as Becquerel rays, and any substance emitting Becquerel rays is said to be radio-active. Not long afterward Madame Curie, in a series of investigations, discovered that the mineral pitchblende, the ore of uranium, was much more radio-active than uranium itself. This suggested that

pitchblende contained something besides uranium to which it owed its radio-activity. After much laborious investigation she discovered that the radio-activity of pitchblende was due to a new and very rare element which she named *radium*. The difference between the X-rays and Becquerel rays is clearly shown by the fact that, of the two, only the Becquerel rays are acted upon by a magnet. By this means the Becquerel rays may be separated into three distinct constituents. The compounds of radium continuously emit light, as can be noticed by observing them in the dark. When a small particle of radium is placed near a screen of zinc sulphide, the radiations striking upon the screen produce countless flashes of light, a process which continues indefinitely. This is beautifully shown in Crookes's spinthariscope (Fig. 429).

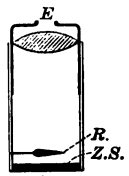


Fig. 429. — Crookes's spinthariscope. The radium compound is on *R*. The flashes of light may be seen through the eyepiece *E*.

305. **On the Electric Theory of Matter.** — According to this theory, the atoms of hydrogen, iron, mercury, and other chemical elements differ from each other in the number of electrons which are contained in each atom, associated with a definite positive charge. In hydrogen there are about 800 or 1000 electrons to the atom, in iron about 56 times, and in mercury about 200 times as many. If all atoms have the same volume, it must follow that these electrons are much more closely packed in some kinds of atoms than in others. In such atoms as those which constitute the elements uranium and radium the electrons are crowded together so closely that now and then an electron flies away. It is easy to see that from the countless millions of atoms in a visible portion of these substances there would be a sufficient number of escaping electrons to produce a continuous bombardment as shown by the spinthariscope. This flying off of electrons constitutes spontaneous radio-activity, or the rays discovered by Becquerel.

"Matter appears to be composed of positive and negative electricity, and nothing else. All its newly discovered as well as all its long-known properties can be thus explained; even the long-standing puzzle of cohesion shows signs of giving way. The only outstanding still-intractable physical property is gravitation. I doubt, however, if its solution is far away" (Sir Oliver Lodge).

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¶ The REVISED TEXT-BOOK OF GEOLOGY is here brought down to the present time as regards its facts, but it still expresses the views of its distinguished author. While the general plan and the distinctive features have been preserved as far as possible, a few important changes have been made relating mainly to zoölogical and botanical classifications, to the bearings of geology and paleontology upon the theory of evolution, and to metamorphism. The order of the grand divisions of the science, physiographic, structural, dynamical and historical, remains the same as in previous editions.

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¶ The limitations of the pupil, and the restrictions of high school laboratories, have been kept constantly in mind. The treatment is elementary, yet accurate; and the indicated laboratory work is simple, but so designed as to bring out fundamental and typical truths. The hand lens is assumed to be the chief working instrument, yet provision is made for the use of the compound microscope where it is available.

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